GEOPHYSICS

1945

A. I. M. E.

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TECHNICAL PAPERS AND DISCUSSIONS PRESENTED BEFORE THE DIVISION AT MEETINGS HELD AT NEW YORK, FEB. 17–20, 1941; FEB. 9–12, 1942; FEB. 15–18, 1943; FEB. 20–24, 1944; LOS ANGELES, OCT. 15–16, 1942; AUSTIN, OCT. 29–31, 1942; DALLAS, MAY 6–8, 1943; CHICAGO, FEB. 25–28, 1946; ALSO PAPERS SCHEDULED FOR THE MEETING AT NEW YORK, FEB. 19–22, 1945, WHICH WAS CANCELED

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NOTICE

This volume is the fifth of a series devoted to papers and discussions on Geophysics. The five volumes are as follows:

1929, Geophysical Prospecting (Vol. 81, TRANSACTIONS A.I.M.E.)

1932, Geophysical Prospecting (Vol. 97, TRANSACTIONS A.I.M.E.)

1934, TRANSACTIONS A.I.M.E., Vol. 110, Geophysical Prospecting

1940, TRANSACTIONS A.I.M.E., Vol. 138, Geophysics

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Volume 74 of the TRANSACTIONS contains one paper on electrical prospecting.

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FOREWORD

Since the appearance of the last geophysical volume in 1940, a number of technical papers have accumulated from which a total of 38 was selected for inclusion in the volume presented herewith by the Committee on Geophysics.

The papers are arranged in five groups: (1) Case History papers—i.e., discussions of geophysical data in relation to geologic conditions known prior to and encountered after the completion of geophysical surveys; (2) theoretical papers, dealing chiefly with the effects to be expected from assumed depths, geometric dimensions and dispositions of geologic bodies; (3) papers on magnetic and electric properties of rocks; (4) papers on electrical and radioactivity well logging, and (5) papers discussing the problems of geophysical education.

Various circumstances resulting from the war—such as shortage of manpower; curtailment of research by graduate students, commercial and government organizations; diversion of geophysicists to more direct war projects; publicity restrictions and cancelations of scientific and technical meetings—made it difficult to obtain papers of the desired type and quantity. Nevertheless, it has been possible to attain a fair balance of topics in this volume. There are ten papers on case history, eight papers on theory, nine papers on rock properties and well logging, and eleven papers on education.

For the case-history section, the Committee was fortunate in securing, for republication, a composite discussion by the late Donald C. Barton, consisting of four separate but related papers and dealing largely with the interpretation of gravitational anomalies on salt domes. This discussion and a paper recounting the geophysical history of a Louisiana salt dome make up the portion of the case-history section dealing with oil exploration. The remainder and major part is devoted to case histories in mining, reporting, with one exception, on results of magnetic and electrical surveys. The preponderance of case-history papers on mining is not believed to be objectionable, as the publications of the Institute have for some time in the past constituted the most logical vehicle for reports of this kind.

In the theoretical section the majority of the papers are concerned with the interpretation of electrical surveys. One paper deals with magnetic depth determinations and another with geothermal theory. The section on rock properties includes two papers on magnetic susceptibility measurements and one on self-potentials in sedimentary rocks. The topic discussed in the latter is closely related to that taken up by two papers in the next section on well logging, which also includes two abstracts of papers on resistivity logging, previously published in Petroleum Technology.

It is debatable whether or not so much material should have been included in the last section, dealing with Geophysics Education. It seems that education shares with politics and religion the doubtful

distinction of provoking the most expansive discussions, some well qualified and some not so well qualified, the debatable issues increasing in inverse ratio to the known facts. The argument probably will not be settled until it is agreed that one type of curriculum is required for geophysical science and another for geophysical engineering or exploration. Be that as it may, it is well to point out that the Institute more than any other geophysical organization has for some time past thrown the doors wide open to a free debate on the subject, and has made its media of publication generously available to present all possible sides of the argument, no matter how controversial.

Viewing the publications in this volume from the standpoint of the accomplishments of the profession in the interval elapsed since the publication of the last geophysical volume, it is noted that most of them reflect essentially a prewar level. During the war, research in geophysical exploration remained virtually at a standstill, while the volume of field activities by industrial and governmental organizations reached unprecedented heights. Along with other sciences and professions, educational institutions lost about all their geophysical students for one academic generation, and it will take about the same time to bring up another to the senior and graduate level. Geophysicists in educational, commercial and governmental lines of endeavor responded freely to the call and made important contributions, directly and indirectly, to the war effort. Direct applications of geophysical knowledge included the search for strategic and critical minerals; meteorology in all its ramifications; applications of magnetic techniques to the de-Gaussing of ships and the detection of submarines from the air; uses of electrical prospecting techniques in the location of land mines, and employment of seismic equipment in sound ranging, aircraft testing and the scoring of practice bombs. Among the more indirect contributions of geophysicists to the war effort are several notable developments in Radar and Sonar proximity fuse, guided missiles, and the location and classification of radioactive materials in connection with the atomic bomb.

It is regretted that the present volume, the first to be published after cessation of hostilities, gives no indication of the manifold and interesting contributions by the geophysicist to the winning of the war. Publicity restrictions are but gradually lifted, and probably more time should elapse before a discussion is published presenting the subject in proper perspective and detail.

In conclusion, the chairman wishes to take this opportunity to thank the members of the Committee for their cooperation in the geophysical activities of the Institute during the difficult war years and for their assistance in the preparation of this volume.

C. A. HEILAND, *Chairman*,
Committee on Geophysics.

DENVER, COLORADO
November 15, 1945

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The Geophysical History of Darrow Dome, Ascension Parish, Louisiana

By J. Brian Eby,* Member A.I.M.E., and T. I. Harkins†

(New York Meeting, February 1942)

Abstract

This paper outlines the geophysical investigation of the area covering the Darrow salt dome, Louisiana. Surveys with the refraction seismograph and torsion balance failed to disclose the dome, but reflection dip shooting was successful and was confirmed by later drilling.

Introduction

The Darrow salt dome and oil field lies in western Ascension Parish, Louisiana, on the outside of a sharp bend and on the east bank of the Mississippi River. The dome occurs about 30 miles south of Baton Rouge and 80 miles northwest of New Orleans. Its geology, shape and structure have been ably described in detail by Carroll E. Cook[1] and, except for the general features, will not be repeated here. The purpose of this paper is to record some of the interesting and pertinent geophysical data contributing to the discovery of the dome and eventually the oil field.

The salt dome is circular in outline and comes to within about 4625 ft. of the surface. At this depth the diameter of the salt plug is approximately 4800 ft. The dome has only a thin cap rock of less than 75 ft. Some oil has been found and is being produced in Miocene sands above the cap rock, but most of the field's production comes from a narrow ring of wells around the east and south flanks of the dome. Producing horizons on the flank are found at 5670 to 5840 ft. in the Miocene and 6890 to 6985 ft., 7028 to 7060 ft. and 8260 to 8270 ft. in the Oligocene. The deepest well that has been drilled is the Humble Oil and Refining Company's Community B-5, on the south flank of the structure, which reached a depth of 10,013 feet.

The size and shape of the field and the area of production are indicated on Fig. 1. The line showing the area of production encloses all wells now producing and all abandoned producers, both on the top and flank of the dome. This line of production is shown on all subsequent geophysical maps as a direct means of comparing the early geophysics to later drilling development.

Darrow dome occurs on the low, flat flood plain of the Mississippi River; it is protected from flood overflow by high artificial levees. The rich loamy soil supports a high degree of cultivation, principally sugar cane. Drainage is secured by many small canals and the water table of the area is at or near the surface. These particular conditions of topography, drainage and top soil greatly influenced the early geophysical picture, and the influence was always unfavorable.

Surveys with Refraction Seismograph and Torsion Balance

A reported oil show in a water well drew attention to the lands of the Belle Helene

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Manuscript received at the office of the Institute March 31, 1942. Issued as T.P. 1495 in Petroleum Technology, July 1942.

* Consulting Geologist, Houston, Texas.
† President, Independent Exploration Co., Houston, Texas.

[1] C. E. Cook: Darrow Salt Dome, Ascension Parish, Louisiana. *Bull.* Amer. Assn. Petr. Geol. (1938) **22**, 1412–1422.

Sugar Co. in 1927, and leases were taken by the Union Sulphur Co. and Gulf Refining Co. The Belle Helene Sugar Co. property is a few miles north of the present known

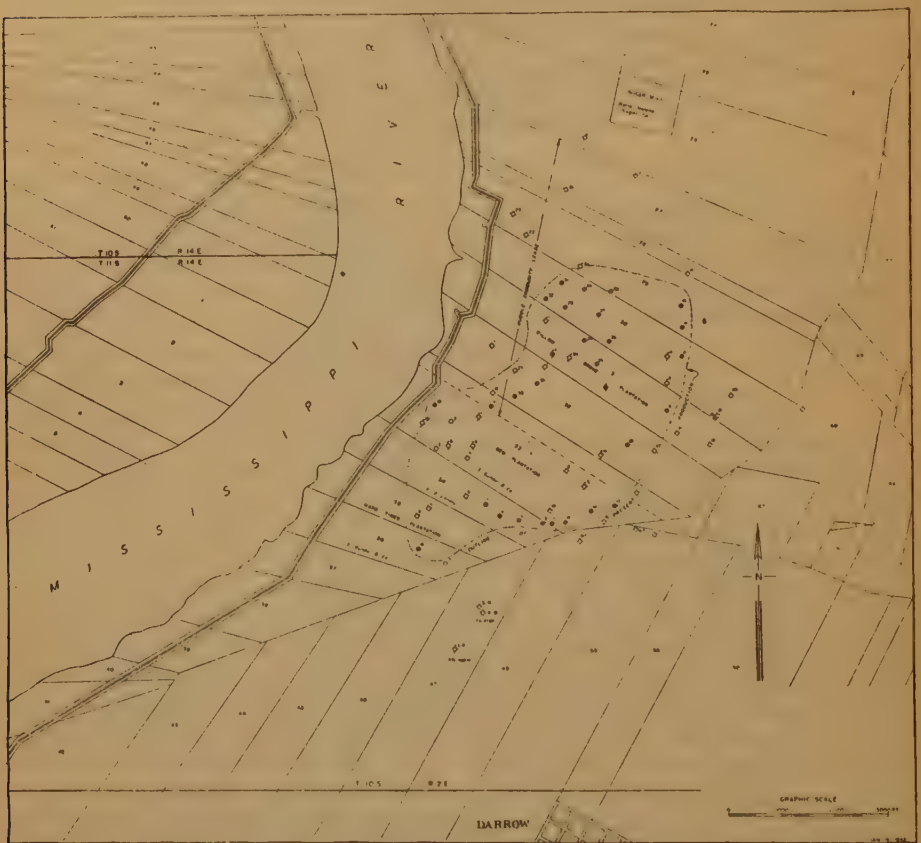

FIG. 1.—DEVELOPMENT MAP OF DARROW DOME, ASCENSION PARISH, LOUISIANA.

dome. Following this leasing program, the Gulf brought in both refraction seismograph and torsion balance to try to define a dome.

At that time (1927 and 1928) the eastern Louisiana Gulf Coast area was undergoing an intensive competitive geophysical examination. Many major oil companies and operators had refraction seismograph and torsion balance crews in operation. Any evidence of specific block leasing by any one company was a signal for other oil companies to enter into competitive geophysics and leasing. The situation at Darrow, however, was one of such relative inaccessibility for geophysical instruments that the block was acquired practically intact by Union and Gulf before any material geophysical information became available to anyone, the Union and Gulf included.

As a result of repeated refraction shooting and gravity work in 1927 and early 1928, the impression persisted that Darrow was a dome but failed of definition. One of the first refraction seismograph reports of this area, dated early in 1927, made the interesting comment that there seemed to

be a domelike uplift of the deeper formations, which appeared to be shaped like a ridge. The ridge was reported to be very small in its east-west extension, but its longer axis ran about parallel to the Mississippi River. This investigation did not warrant the assumption of a deep dome, as the degree of the disturbance was very slight.

By March 1928, out of the many geophysical attempts to outline a salt-dome structure at Darrow, there emerged a so-called torsion balance picture and an area of refraction seismograph interest. These interpretations are combined on Fig. 2, showing several closing gravity isogals and one enclosing refraction line. The authorships of both outlines are unknown and are given here partly as evidence of the activity of scouting departments and partly to attest the general reliability of early geophysical indications, where both methods tended to confirm one another. The gravity map shown in Fig. 2 is believed to be in tenths of milligals and the refraction outline was supposed to be the 5000-ft. contour on salt.

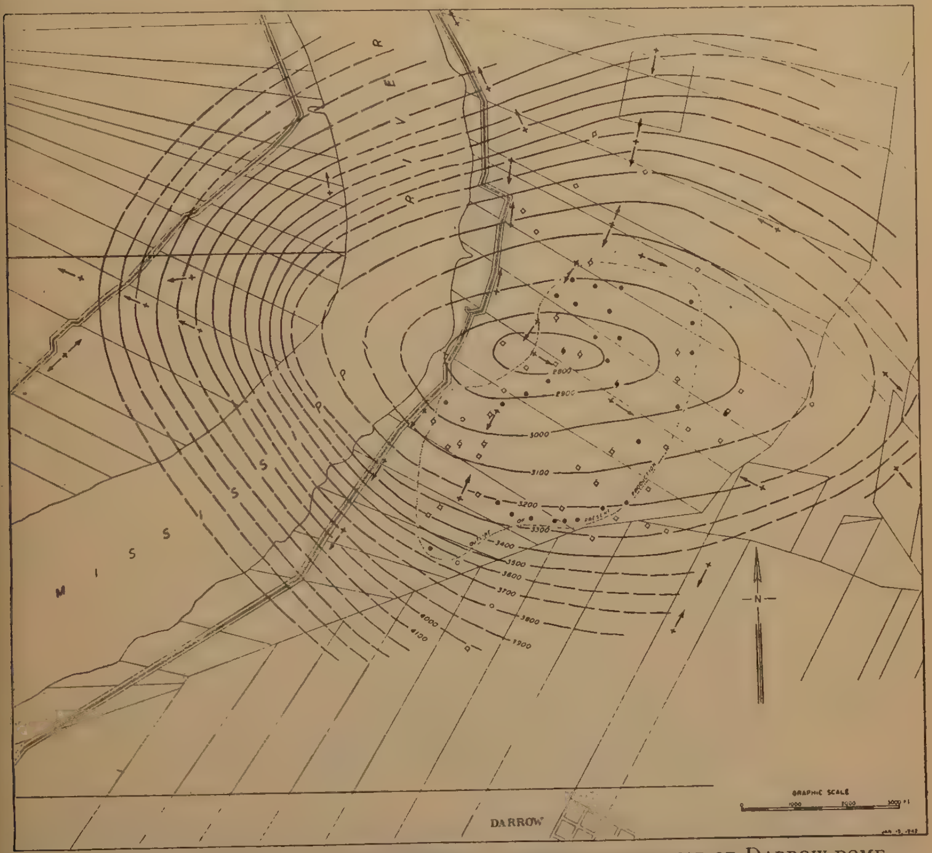

FIG. 2.—REFRACTION SEISMOGRAPH AND EARLY TORSION BALANCE MAP OF DARROW DOME.

A complete torsion balance picture of Darrow dome and vicinity, made before the dome was proved by drilling, is given by Fig. 3, which was compiled from data furnished by Gulf Refining Co. The gravity picture shows all gradients obtained by the survey and isogal lines are indicated, the

solid lines representing $\frac{1}{10}$ milligal and the dotted lines $\frac{1}{5}$ milligal. The outline of present production shows the dome to lie no stations in the area covered by the river. The closure from the lowest isogal to the west is 7 milligals. The further increases of

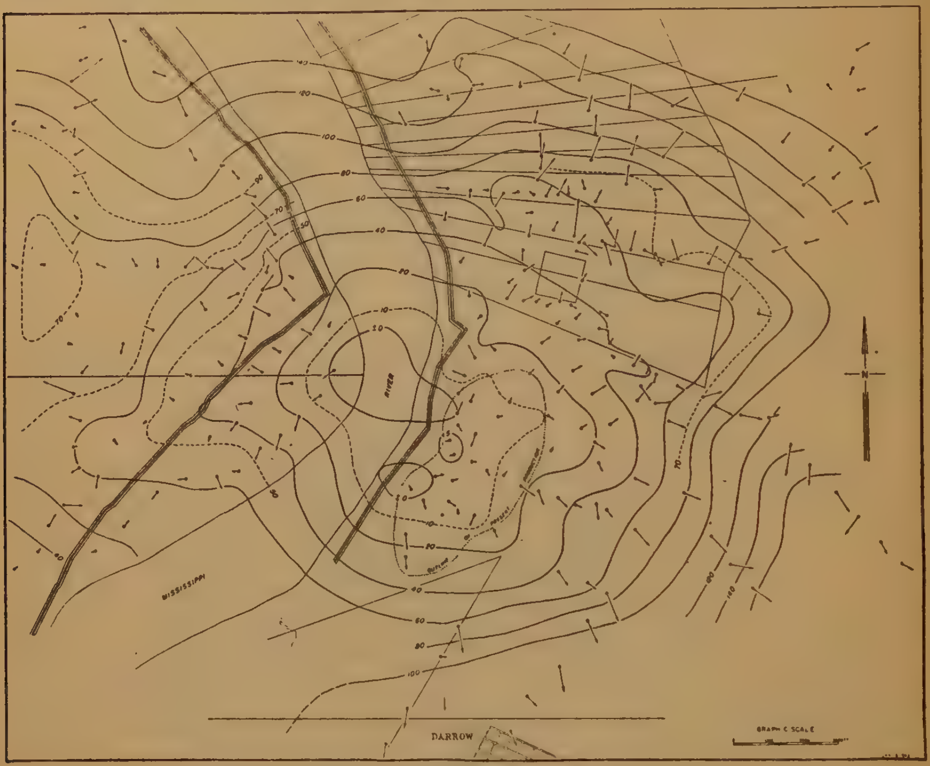

FIG. 3.—TORSION BALANCE MAP OF DARROW DOME.

almost exactly in the center of the gravity minimum.

At the time of the Darrow torsion balance investigation, December 1927 to May 1928, very little was known about the influence of regional gravity. The Sorrento dome near by had already been discovered, and it was recognized that at Sorrento there was a greater gradient flight both north and south than would be expected from the dome picture, so that it could have been guessed that Darrow was in a regional gravity minimum of great width. The construction of the isogals at Darrow was somewhat arbitrary because there could be gravity on the north, east and west were subsequently found to represent regional effects.

Since neither the refraction seismograph nor the torsion balance produced clear-cut positive evidence of the occurrence of a salt dome at Darrow, it was realized that other methods would have to be tried out to determine the true situation. Reflection seismograph work had not yet been attempted in the Gulf Coast, and because of lease considerations the Gulf drilled a well to 5606 ft. in sec. 27, just south of the Belle Helene Sugar Mill (well in sec. 27 marked No. 1 on Fig. 1). This well did not find any

dome indications. A well was drilled in the west part of sec. 32 (see well marked No. 1 on Fig. 1) to a depth of 3780 ft., but this also failed to disclose the dome.

reflection method before the work at Darrow was started.

The area represented a difficult problem for reflection shooting, for two principal

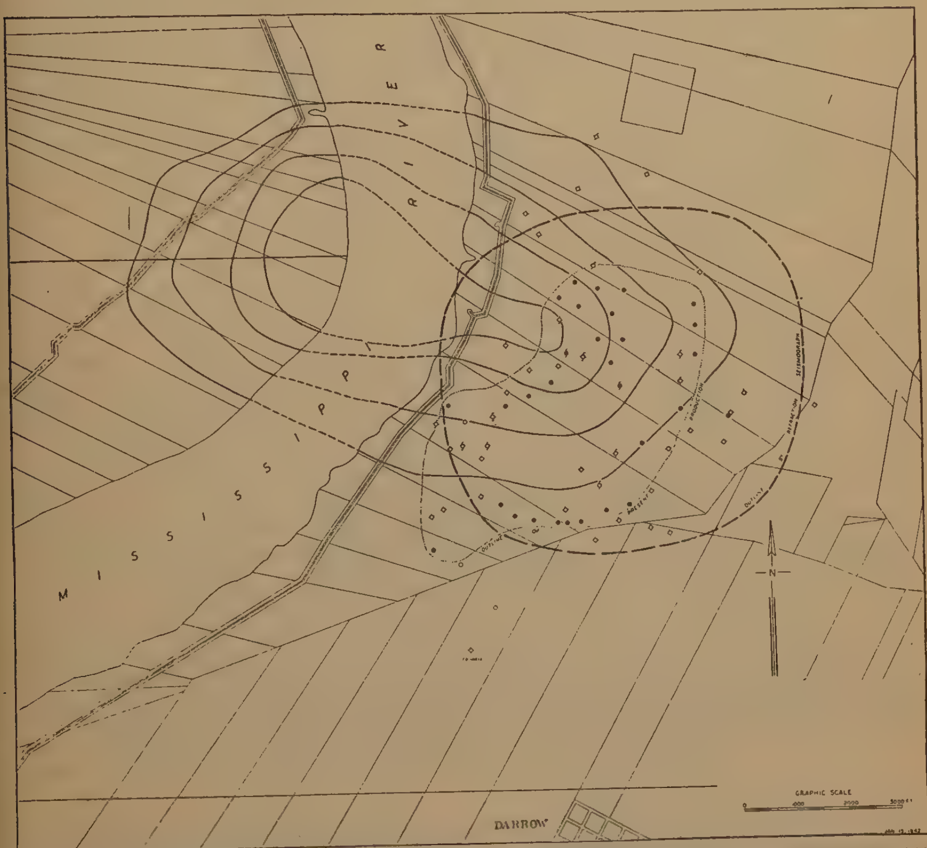

FIG. 4.—REFLECTION SEISMOGRAPH MAP SHOWING DIRECTION IN WHICH PROFILES WERE SHOT AND CONTOURS DEDUCED FROM RECORDS.

REFLECTION SURVEYS

In order to try out on the Gulf Coast the reflection technique that had been developed by the Geophysical Research Corporation in Oklahoma, the junior writer's crew, which had been making refraction surveys in New Mexico, was equipped in the summer of 1929 with reflection apparatus, remaining under the supervision of Mr. E. McDermott and in the employ of the Gulf. Some two months were spent on the investigation of other prospects by the

reasons: (1) the very soft nature of the surface alluvium, which absorbed much energy; (2) the fact that the formations for several thousand feet below the surface were also soft, consisting of sands and clays; the sands varying in thickness rapidly in short distances, and apparently containing none of the hard rock interfaces that had served as reflecting horizons in Oklahoma.

Up to this time it was thought that the only way to make use of reflections was to

obtain prominent or persistent reflections that could be correlated. This was found to be almost impossible in most of the Gulf Coast area worked, so it was necessary to obtain some aid for the correlations.

At Darrow, for the first time, reflection shooting (Fig. 4) was attempted where, unknown to the geophysical party, there were very steeply dipping beds; that is, the salt flank and the sediments above it. The field method used was to set detectors first in one direction from the shot point and then in the opposite direction. In this area the first setup was along the highway, so that the two opposite directions were nearly north and south, and at a position on the south flank of the dome.

In the method just described, the reflection time of arrival at more distant detectors should be greater than those nearer to the shot point, and if the reflection horizons are horizontal, the times on both lines from the shot point would show similar time differences between the reflection arrivals at near and distant detectors.

FIG. 5.—REFLECTION RECORDS, SHOOTING FROM TWO DIAMETRICALLY OPPOSITE DIRECTIONS.

On this location at Darrow, however, the reflections on the north line actually showed less time for the far detector than for the near one, and the reflections on the south line showed much greater difference in reflection time between near and far detectors than is normal for the over-all time. This can be due only to a steep south dip on the reflecting horizon.

None of the records obtained in this area was available at the time this paper was written, but Fig. 5 is included to show four reflection records taken in an entirely

different area with modern reflection equipment. The two shot points in this figure were shot in diametrically opposite directions, and in each case strong northeast dip was found. There is a negative differential time on the record shot to the southwest, and an excessive differential time on the records shot to the northeast. In other areas investigated, negative differential times had been noted but had been attributed to differential weathering or timing variations, as only two-element oscillographs had been used up to a few months previous to this time. With the use of the multiple-element oscillograph, it was possible to record four or five different geophone (detector) positions on a single record, as in the records of Fig. 5.

An effort was made in this investigation to correlate all reflections obtained with the aid of differential times. That this was successful is shown by the reflection contours shown on Fig. 4 in connection with the outline of present production. No deep reflection information, and not only proved the dome but is the highest salt well drilled in the field to this time. The Rio Bravo well was completed Sept. 26, 1932, nearly three years after the reflection investigation. The accompanying list of wells indicates the chronology of all wells drilled immediately prior and subsequent to the reflection work, and the results of such drilling. This is visible evidence of the successful application of this method of geophysics.

Relative Merits of Three Methods

The authors believe the Darrow reflection survey to be of real historical interest, because it marked the first step in the development of dip shooting, and because the quality of this type of work was good enough in this early stage to be confirmed so accurately by later drilling. In appraising the relative merits of the three types of geophysics used at Darrow dome, the reader must think back to the period during

Chronological List of Wells Drilled on or in Vicinity of Darrow Dome

July–August 1929

Prior to reflection shooting as shown on Fig. 4	
Big Dome Oil Co., Rearwood No. 1	4880 ft. T.D. No dome material
Gulf Refining Co., Belle Helene No. 1	5605 ft. T.D. No dome material
Belle Helene Oil Co., D. Breaux No. 1	3780 ft. T.D. No dome material
Subsequent to reflection shooting as shown on Fig. 4	
Rio Bravo Community No. 1	4035 ft. oil-salt; 4677–4900 ft. T.D.
Rio Bravo Community No. 2 (Humble)	4846 ft. top salt; 4861 ft. T.D.
Rio Bravo Gumbel No. 1	6025 ft. top salt 6052 ft. T.D. salt
Gulf Ref. Co., Community No. 1	4683 ft. top salt 4883 ft. T.D. salt
Humble Oil & Ref. Co. Community No. 1	4627 ft. No dome material
Humble Oil & Ref. Co. Gumbel No. 1	5781 ft. No dome material
Humble Oil & Ref. Co. Community No. 5	5674 ft. top salt 5684 ft. T.D. salt
Humble Oil & Ref. Co. Gumbel No. 3	5948 ft. No dome material
Humble Oil & Ref. Co. Community No. 6	5686 ft. No dome material
Humble Oil & Ref. Co. Gumbel No. 4	6033 ft. top of salt 6645 ft. T.D. salt
Humble Oil & Ref. Co. Community No. 8	5636 ft. No dome material
Humble Oil & Ref. Co. Gumbel No. 5	6841 ft. top salt 6901 ft. T.D. salt
Humble Oil & Ref. Co. Community No. 9	5418 ft. top salt 5715 ft. T.D. salt

reflections were found around what is now known to be the top of the dome.

The first well drilled after the completion of the reflection picture, the Rio Bravo Oil Company's Community No. 1, found Miocene oil at 4025–4035 ft. and topped the salt at 4627 ft. This well was drilled on which the work was done. The fact that refraction shooting showed acceleration in one direction and not in another did not conform to all previous dome structures, which showed acceleration in all directions. It was not until later, for example, that refraction work over Goose Creek oil field,

Harris County, Texas, showed as much as a tenth second acceleration in one direction and none at all in other directions. This is not the place to explain such anomalies, but to point out that they do exist over some known structures.

In defense of refraction work and the torsion balance, however, it must be pointed out again that the lack of accessibility of the area as a whole and the poor top and subsoil conditions considerably handicapped these services at Darrow. Nevertheless, both did give some, if not satisfactory, dome indications. The significance of the work on Darrow is that it was there that reflection dip shooting was initiated in the Gulf Coast area and proved successful.

Case Histories and Quantitative Calculations in Gravimetric Prospecting

(New York Meeting, February 1944)

CONTENTS

Introduction

OF the four papers that comprise this TECHNICAL PUBLICATION, three are case histories of individual geophysical prospects, subsequently tested by drilling.

The bibliography of Dr. Barton's published scientific papers† includes investigations in physiography and surface geological mapping, as well as his geophysical papers, and from this list it is to be observed that he early recognized the place of different types of geophysical prospecting methods in the search for geological structures of economic importance. Moreover, his viewpoint was not merely that the structures should be found, but that the geophysical data should be examined quantitatively to determine the geometry of the structures. In other words, that although these data are insufficient to deduce a unique form for the structure that caused the effects measured in the data, the engineering computations should be carried out to give as much of a definite configuration to the structure as the data permitted, in order that the testing of the structures could be conducted in the most economical manner and with the idea that the experience so gained could be later incorporated in the study of structures subsequently found.

Dr. Barton continually emphasized the quantitative use of geophysical observations, whereas at the time that he began his specialization in geophysics it was considered sufficient to use observations only qualitatively. He, more than any one else, was responsible for the first volume on geophysical prospecting issued by the Institute in 1929, and his three articles in that volume stressed the quantitative use of geophysical prospecting.

The fourth article in this present TECHNICAL PUBLICATION is a further contribution to this branch of geophysical interpretation, and is a supplement to the paper in the 1929 volume, "Calculations in the Interpretation of Observations with the Eötvös Torsion Balance."

From the successful demonstration by Dr. Barton of the usefulness of quan-

Issued as T.P. 1760, November 1944.

* Died July 9, 1939.

† Memorial by Wallace Pratt in the *Bulletin* of the American Association of Petroleum Geologists (December 1939) 1888–1896.

titative interpretations, it followed that there was an insistence of greater accuracy in the data and a thorough understanding of the disturbing transients and extraneous factors that are present as a background in the field mapping; he therefore was a pioneer in the improvement in the accuracy of measurements indicated as necessary in different problems in geophysics. He recognized and insisted upon the proper place of statistical methods in the examination of groups of data, including the application of least-square adjustments of these groups.

He understood all types of geophysical prospecting, and on individual surveys he made measurements with different instruments of the variation of different physical properties, and demonstrated that quantitative calculations regarding a structure based on the variation of a single physical property were much less useful than the computations based on data from independent measurements of several physical properties.

He further pointed out the value of the quantitative studies in variations of physical properties of crude oils from different horizons in the same district, or in the same oil field, as a line of investigation suitable for the study of the metamorphism of oil and its migration underground. In the latter field he did not carry the investigations sufficiently far to formulate any hypothesis regarding metamorphic alterations and the migration of crude oil, but he showed in this field also the importance of quantitative measurements in the same way that he demonstrated their importance in geophysical prospecting. Dr. Barton therefore applied to the field of geophysics the methods of the engineer, and the Institute furnished the vehicle for the first exposition by him of this engineering viewpoint, in the volume "Geophysical Prospecting" published in 1929.

PAUL WEAVER.

HOUSTON, TEXAS,
July 18, 1944.

Gravity Anomalies of Nash and Damon Mounds, Fort Bend and Brazoria Counties, Texas

BY DONALD C. BARTON*

THE Nash and Damon Mound salt domes lie 5 miles apart, 50 miles southwest of Houston.

Nash.—Nash is an average shallow Gulf Coast salt dome. Its diameter is one mile. The depth to the top of the cap is 620 ft. and to the top of the salt, 920 ft. Within the depth of drilling, the flanks are steep to vertical. A 5-ft. topographic mound is present.

Nash was the first Gulf Coast salt dome to be discovered by geophysics. Attention had been called to it by H_2S in the water of three water wells 40 to 70 ft. deep. On the basis of that sulphur water and the faint suggestion of a salt-dome mound, the chances of the presence of a salt dome were rated at five out of one hundred. The torsion balance survey of Fig. 1 was made in February-March, 1924, and the presence of the salt dome was established with a probability of better than 99 out of 100.*

Damon Mound.—Damon Mound† is one of the larger shallow Gulf Coast salt domes. Its diameters are 1.2 and 1.8 miles. The

Published by permission of the Humble Oil and Refining Co. Paper was written in July 1937.

* Humble Oil and Refining Co., Houston, Texas. (The author was a member of the A.I.M.E. from 1920 until he died, on July 9, 1939.)

* D. C. Barton: Eötvös Torsion Balance Method of Mapping Geologic Structure. Geophysical Prospecting, 1929, 444–446. A.I.M.E. 1929.

† For a published description of Damon Mound see George M. Bevier: The Damon Mound Oilfield. Geology of Salt Dome Oilfields, 613–643. Amer. Assn. Petr. Geol. 1926.

top of the cap lies 70 ft. below the surface of the mound and approximately at the general level of the surrounding area. The depth to the top of the salt is 575 feet.

A conspicuous topographic mound rises 75 ft. above the general level of the area. Within the depth to which drilling has gone, the flanks of the salt core are steep to vertical except on the southwest. Damon Mound has been known since the days of the first settlers.

Stratigraphic Section Pierced by Domes

The stratigraphic section through which the Nash and Damon Mound salt domes rise presumably comprises at least 20,000 ft. of sedimentary beds, mostly sands, clays and shales.* Drilling has gone to a depth of 8115 ft. at Pledger, only a few miles to the southwest, and 400 ft. down the regional dip from Damon Mound, and has not penetrated the Frio (Oligocene). The thickness of the rest of the section down to the base of the Wilcox (Eocene), according to Teas and to McCarter and O'Bannon, should be more than 8800 ft.; and the thickness of the Midway (Eocene) should be more than 600 ft. The depth to the base of the Tertiary, therefore, should be at least 18,000 feet.

The salt domes of the Gulf Coast are known to be older than late Upper Cretaceous, for cores of Navarro chalk (uppermost Upper Cretaceous) have been recovered from the edge of the cap on the South Liberty dome. The age of the salt is believed rather commonly to be at least pre-Upper Cretaceous and more probably either pre-Lower Cretaceous or possibly lowermost Cretaceous. The thickness of the Upper Cretaceous farther inland is known to be at least 2500 ft. Unsurmised great southward thickening of the Lower Cretaceous in northern Louisiana and southern Arkansas has been disclosed by recent deep drilling in southern Arkansas and northern Louisiana, and the salt in Arkansas is known definitely to be at least lowermost Lower Cretaceous in age and possibly Jurassic or older. The thickness of the beds through which these domes rise, therefore, would seem probably to be at least 22,000 ft. in the Nash-Damon Mound area.

Specific Gravity Relations

The specific gravity of the beds increases from 1.9 ± 0.1 at the surface, probably to 2.7 at very great depth. Determinations of the specific gravity of numerous cores show that: (1) at Raccoon Bend the specific gravity increases linearly from 2.1 at the surface to 2.47 at 7000 ft. in the Cook Mountain (Eocene); and (2) at Dickinson from 2.0 near the surface to 2.4 at 9100 ft. in the Frio (Oligocene). Raccoon Bend lies considerably updip, and Dickinson considerably downdip from Nash and Damon Mound. The rate of increase of the specific gravity downward at their locale should be intermediate between the rates at Raccoon Bend and Dickinson.

The specific gravity of the salt is 2.16 to 2.22, depending upon the amount of included anhydrite.

Nash Anomaly

The Nash gravity anomaly consists of a small but sharp and well defined maximum and a broad indistinct minimum. The anomaly taken as a whole is much obscured by a large regional increase of gravity southward and by the effects of the adjacent Damon Mound, West Columbia, Lochridge, Long Point, and Rabbs Ridge minima.

The maximum has an amplitude of 1.5 milligals. It is very slightly larger in area

* D. C. Barton, C. H. Ritz and M. Hickey: Gulf Coast Geosyncline. *Bull.* Amer. Assn. Petr. Geol. (1933) **17**, 1446–1458. Also Gulf Coast Oilfields. Amer. Assn. Petr. Geol., 1936, 192–204.

See also H. V. Howe and C. K. Moresi: Geology of Iberia Parish, Louisiana. Louisiana Dept. of Conservation *Geol. Bull.* No. 1 (1931) 86–91.

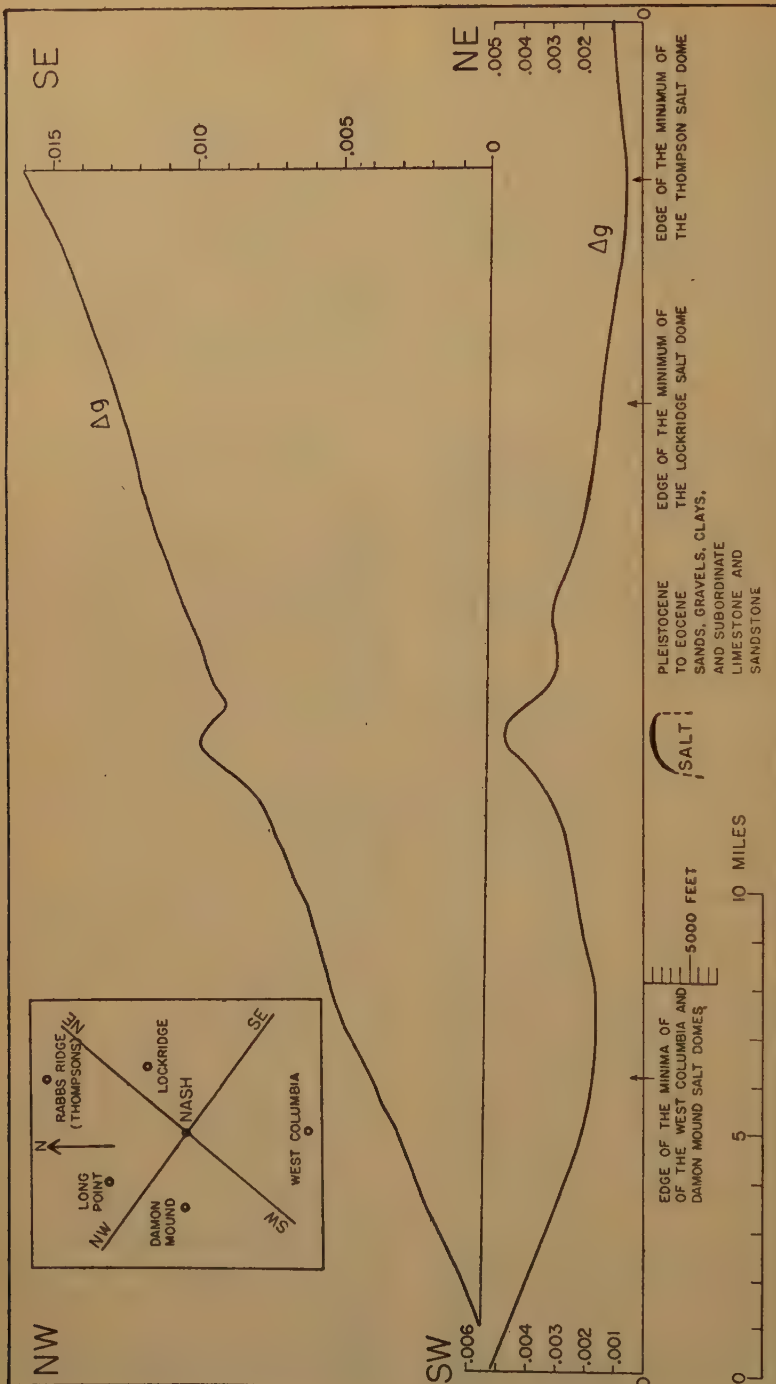

FIG. 1.—NORTHWEST-SOUTHEAST AND NORTHEAST-SOUTHWEST PROFILES OF RELATIVE ANOMALOUS GRAVITY ACROSS NASH SALT DOME, FORT BEND AND BRAZORIA COUNTIES, TEXAS.

than the top of the dome but because of the regional variation of gravity its limits are poorly defined. The gradient in the zone of maximum amplitude over the edge of the cap ranges around 17 E. The maximum at Nash is wholly the anomaly of the cap-rock mass. The latter's specific gravity of 2.5 to 2.6 contrasts strongly with the specific gravity of 2.0 to 2.05 of the beds at the same depth. Being a relatively heavy mass at shallow depth, the cap rock produces a sharp maximum, which coincides fairly closely in position and area with the cap rock. But as the base of this rock lies at a depth of 900 ft. over the central part of the dome, and as a fairly thick mass of cap extends 1500 to 2000 ft. down the flank, at least around part of the circumference of the dome, the maximum is 2000 ft. radially wider than the cap rock.

The Nash salt dome happens to lie in a critical location, so that its minimum is effectively concealed by adjacent minima. Nash is centrally located between the Damon Mound, West Columbia, Rabbs Ridge, Lochridge, and Long Point salt domes. The minima of the first three are large in area and in amplitude, and that of the fourth is fair sized. The resultant effect of these minima is to produce a large maximum in the central area between the domes. The maximum is shown distinctly in the SW.-NE. profile of Fig. 1, and the tendency toward it can be recognized in the NW.-SE. profile. The potential minimum of the Nash dome is approximately concentric with that maximum. Being rather weak, the minimum effect of the Nash dome serves mainly to flatten the maximum and produces only a faint trace of a recognizable minimum in the picture of observable gravity.

The presence of the trace of a minimum can be recognized in the profile of Fig. 1. The indication of the minimum in the profiles is not definite enough for any estimate of its amplitude. Its presence is brought out more clearly if a study is made of the elimination of the Damon Mound, West Columbia, Lochridge, Rabbs Ridge and Long Point minima. The elimination of plausible assumed minima for these anomalies builds up an average Gulf Coast salt-dome minimum at Nash in the residual isogams.

A regional Eötvös gradient of 4.4 E is present in the Nash area (Fig. 1) and aids in obscuring both the presence of the minimum and the limits of the maximum. The latter, however, has sufficient amplitude and sufficiently sharp form so that it stands out conspicuously above the regional variation.

The presence, position, and depth of the Nash dome were predicted from torsion balance data with good accuracy, entirely in advance of drilling. The gradient arrows of Fig. 2 are the data on which the predictions were based. The inner dashed line represents the presumed position of the edge of the top of the cap, at a predicted depth of 500 to 900 ft., and the outer dashed line represents the presumed position of the 4000 to 5000-ft. contour on the edge of the salt. The cross marks the predicted center of the dome. The dotted contours are structure contours drawn from drilling data on the top of the cap-salt core. The Nash dome was discovered in 1924. I now know how crude my knowledge of interpretation at that date was, and as the result of the subsequent years of experience with torsion balance surveys in the Gulf Coast, I would not attempt as definite a prediction of the position of the edge of the dome without a much more detailed survey.

Damon Mound Anomaly

The Damon Mound maximum-minimum is one of the largest salt-dome anomalies in the Gulf Coast (Fig. 3). Like that of the Nash dome, the Damon Mound anomaly consists of a maximum at the center of a very much larger minimum. The amplitude of the latter is 8 milligals; and its diam-

eter is 15 to 20 miles. The central maximum has an amplitude of 1.2 milligals. Its width minima are in the ratio 2 to 8. If N and D are diameters of their respective bases,

FIG. 2.—MAP OF NASH SALT DOME, SHOWING GRADIENT ARROWS OF TORSION BALANCE SURVEY, PREDICTIONS IN REGARD TO CENTER AND OUTLINE OF DOME, AND STRUCTURE CONTOURS ON DOME FROM SUBSEQUENT DRILLING.

is not quite 2½ miles in contrast to a width of the cap of 1¾ miles.

Flare of the Damon Mound salt core to great depth is indicated by the gravity data. The respective salt cores of the Damon Mound and Nash salt domes presumably are similar in general form, in position with reference to the surface, and in vertical dimension. Their minima, therefore, should vary as their volumes, and their volumes as the respective means of the area of the top and base. The areas of their tops are in the ratio 2.2 to 3.6 and their then:

$$\frac{N^2 + 2.2}{D^2 + 3.6} = \frac{2}{8}$$

If the Nash salt core is an inverted cone, $N = 0$, and D, the diameter of the base of the Damon Mound salt core, is 2.3 miles in contrast to a diameter of 1.9 miles at its top. If the Nash-dome salt core has the same diameter at the base as at the top, the diameter of the base of the Damon Mound salt core must be 3.7 miles, twice the diameter of the top of the salt core.

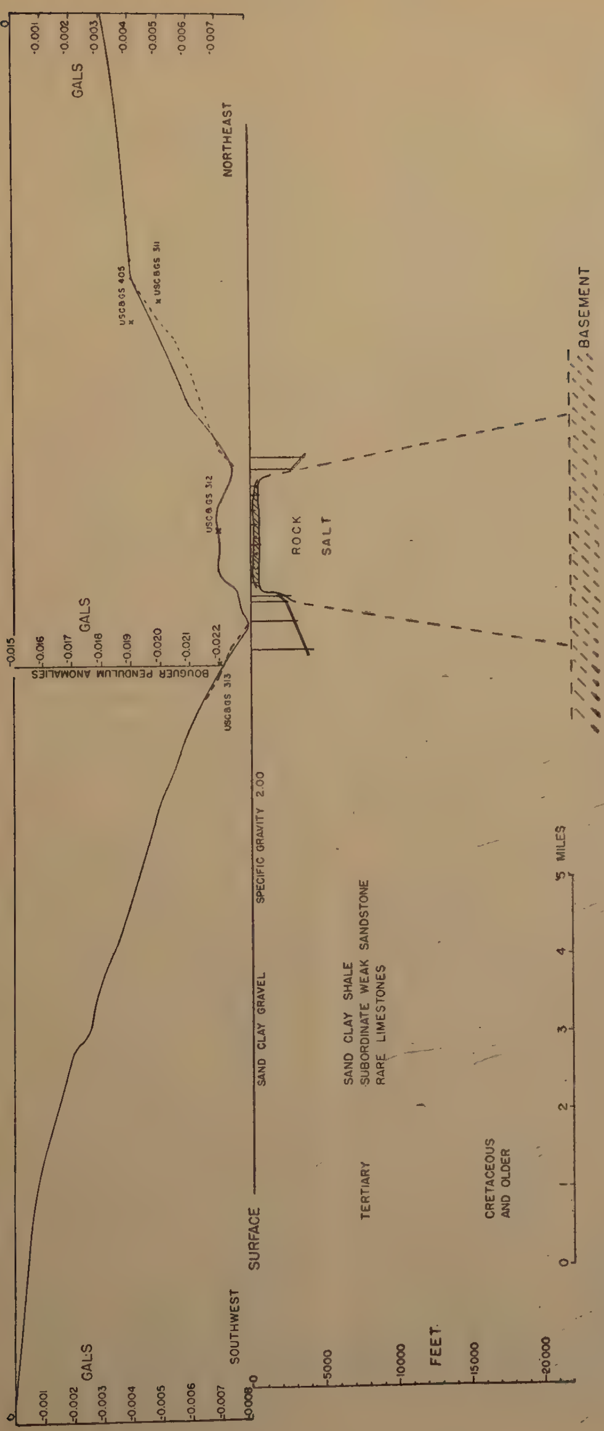

FIG. 3.—NORTHEAST-SOUTHWEST PROFILE OF ANOMALOUS RELATIVE GRAVITY ACROSS DAMON MOUND SALT DOME, BRAZORIA AND FORT BEND COUNTIES, TEXAS.

Relation of Maximum-minimum to Dome

The maximum-minimum form of the gravity anomaly at Nash, at Damon, and at most of the shallow salt domes in the Gulf Coast, is the result of the contrasting effects: (1) of the small, relatively shallow, but relatively very heavy cap-rock mass, and (2) of the relatively light salt core extending at great depth; the maximum being the effect of the cap and the minimum of the salt. The width* of a gravity anomaly commonly extends out from the position of the edge of the causative body for a distance equal to or slightly greater than the depth to the base of the body. Gravity maxima and minima lie concentrically above symmetrical causative bodies. Being shallow and of relatively high specific gravity with reference to contiguous beds at the same depth, and being symmetrical, the cap-rock mass produces a sharp maximum, which is concentric with it and whose width is slightly greater than the width of the cap. Being lighter than the surrounding beds, and being a vertical cylinder or frustum of a cone, the salt core produces a concentric minimum.

As the base of the salt core lies at a depth greater than 4 miles, the width of the minimum commonly is 8 to 10 miles. Because of the amplitude in the width of the recognizable anomaly, the minima of the large domes have greater diameters than those of the domes of average size. Downward flare, such as that surmised for Damon Mound, also increases the width of the anomaly.

The maximum within a minimum may be regarded as the general form of the anomaly produced by Gulf Coast salt domes. Both the maximum and minimum are well developed at Damon Mound. On deep salt domes, the cap rock is deeper, its specific gravity in reference to the surrounding beds is less, and in general, there seems to be less of it. Thus no maximum is found on deep domes, and the anomaly of a deep Gulf Coast salt dome is a minimum without a maximum. On a few shallow domes in the Gulf Coast, such as North Dayton, the respective forms of the maximum and of the crest of the minimum are such that the maximum is compensated out and no gravity maximum is evident even though a fairly thick cap is present at moderately shallow depth. On other domes, such as Nash and Spindletop, the maximum is conspicuous while the minimum is faint and recognizable only by careful study of a good detailed survey.

Nash Anomaly in Torsion Balance and Gravimeter Surveys

The modern torsion balance surveys for deep salt domes, and the gravimeter surveys, in general, will not lead to the discovery of anomalies that are not as large as, or only as large as, the Nash maximum in area and amplitude. The discovery of Nash by the torsion balance has puzzled several geophysicists who are familiar only with the later surveys for deep salt domes, for these later surveys fail to give suggestion of Nash. The reasons why the original survey led to the discovery of Nash, and why the later torsion balance surveys do not lead to the recognition of its presence, are three: (1) The original survey was a detailed survey of a particular prospect, therefore stations were closely spaced; (2) the later surveys for deep domes most commonly are reconnaissance surveys of large areas and the mesh of their traverses is so large that an anomaly of the areal size of the Nash maximum is easily missed; and (3) the geophysicist does not have data enough, or does not make a study

* Mathematically, every anomaly is asymptotic to zero only at plus and minus infinity and therefore is infinite in width. The recognizable width of an observed anomaly varies with the amplitude of the anomaly; for reasonably sharp anomalies, the apparent width presumably is the width of the true anomaly at the level of one to two tenths of the true maximum amplitude.

careful enough, to disclose the faint suggestion of the Nash minimum.

Nash, therefore, is a rather "anomalous" anomaly. It was easily and decisively discovered in the early days of the application of geophysical methods when the geophysicist had little experience with the method and knew very little of its theory. Yet 13 years later, if still undiscovered, Nash would have a good chance of *not* being discovered by the present-day surveys with the method.

Lost Hills, California—an Anticlinal Minimum*

By Donald C. Barton

Geology of Area

Lost Hills lies in Kern County, California, in the southwestern part of the San Joaquin Valley, approximately 12 miles northeast of the southwestern edge.

The San Joaquin Valley is a huge synclinal trough. The central axial part has been deeply filled with alluvium. The southwestern flank is composed of beds that have risen sharply from great depth, which in many areas are sharply folded and faulted. Lesser but nevertheless sharp folding has affected the beds within the valley trough and produced the Kettleman Hills, Lost Hills, Belridge, and Elk Hills anticlines along the southwestern edge of the valley.

Lost Hills is a rather sharp, somewhat asymmetrical, anticline. A low range of hills, the Lost Hills, marks its crest (Fig. 2*A*). The production to date has been shallow and only the structure of the shallow part of the crest is well known from drilling. The deeper structure is known from a few wells and from surveys with the seismic reflection method. In the geologic structure section of Fig. 2*A*, the parts away from the axis of the anticline are based on data from these seismic surveys. The northeastern flank of the anticline is known to be steeper than the southwestern. The strike of the anticline is northwest-southeast, parallel to the general trend of the southwest flank of the valley. The stratigraphic section, according to Kleinpell, is shown on page 10.*

Torsion Balance Survey

The Lost Hills torsion balance survey presented in this paper comprises two northeast-southwest profiles approximately at right angles to the trend of the regional and local structure. The one profile extends from the lowest slopes of the foothills forming the southwestern side of the San Joaquin Valley well across the Lost Hills anticline. The other profile lies about 2 miles to the northwest and extends not quite so far to the southwest but somewhat farther to the northeast, toward the center of the valley.

A map of the gradient arrow, differential-curvature line, showing the results of the survey, is given in Fig. 1. The gradient profile, the differential-curvature profile, the topographic profile and the Δg profile, along the southeastern line of profile are superimposed in Fig. 2 above a generalized structure section of the Lost Hills anticline.

A high degree of correlation between structure and the variation of gravity† is shown by the data of the Lost Hills torsion balance survey in Figs. 1 and 2.

* The torsion balance data were obtained through the courtesy of Paul F. Getty, Inc. The data for the generalized geologic section across Lost Hills were obtained through the courtesy of C. C. Gester, Standard Oil Company of California and L. C. Decius, Associated Oil Co. The paper was written in July 1937.

* H. W. Hoots and S. C. Herold: Natural Gas Resources of California. Geology of Natural Gas, 126, Amer. Assn. Petr. Geol., 1935.

† The gravity and the gradient shown by a torsion balance survey are the relative gravity and horizontal gradient referred to any common elevation within the common range of elevation of the area, and corrected for variation with latitude. The gravity essentially is relative Bouguer gravity.

Stratigraphic Section

Pleistocene	Tulare formation	fresh-water sandstones and clays	± 200 ft. (?)
Pliocene	Etchegoin group	clays, siltstones sandstones	(?) missing on top of the structure
	San Joaquin clay	mainly marine	
	Jacalitos formation	marine sandstones and siltstones	500 ft.
Miocene	Monterey group	marine siltstone	
	Reef Ridge formation	and diatomaceous shale	700 ft.
	McLure shale	siliceous and argillaceous brown shale and siltstone	2400 ft.
		Regional unconformity	
	?	fine sandstone, brown shale	700 ft.
	Temblor formation	marine sandstone, and thin brown clay shale	900+ ft.
		Regional unconformity	
Oligocene	Wagonwheel formation	shale	not reached as yet
Eocene	Kreyenhagen shale	siliceous and argillaceous brown shale, siltstone	not reach as yet
	Avenal sandstone	massive sandstone and thin interbeds of shale	not reached as yet

Regional Anomalies and Structure

As is evident in Figs. 1 and 2, the regional variation of the gradient of gravity and of the differential curvature reflect the regional major structure. They indicate the huge synclinal trough filled deeply with relatively light sediments, and that the southwestern flank is composed of older and relatively heavier beds rising sharply from great depth. The general form of the Δg profile agrees with the general form of the topographic profile, and the topography strongly reflects the major structure. A small southwestward regional gradient is present in the northeastern third of the survey. This regional gradient increases southwestward and becomes extremely large near the edge of the valley. In the wide central part of the San Joaquin Valley the basement is very deep, and although the beds are not flat-lying, they have no marked regional dips. Thus a small regional gradient or none at all should be expected. But near the edge of the valley, where the older and denser beds are rising from the depths, a gradient toward the edge of the valley is to be anticipated; and since the beds of the flank do come up sharply from great depth, large gradient values should prevail at the edge of the valley.

The gradient and differential curvature of the southeastern profile agree in indicating that the edge of the valley is marked by two large faults down-thrown to the northeast. The southwestern edge of the valley in places is known to be marked by large faults, but as far as the writer knows, geologic data in regard to the presence or absence of these two faults are not available. They would seem to lie under the coalescing alluvial fans of the southwestern edge of the valley and data in regard to them may be difficult to obtain.

An east northeast-west southwest regional differential curvature is present. It

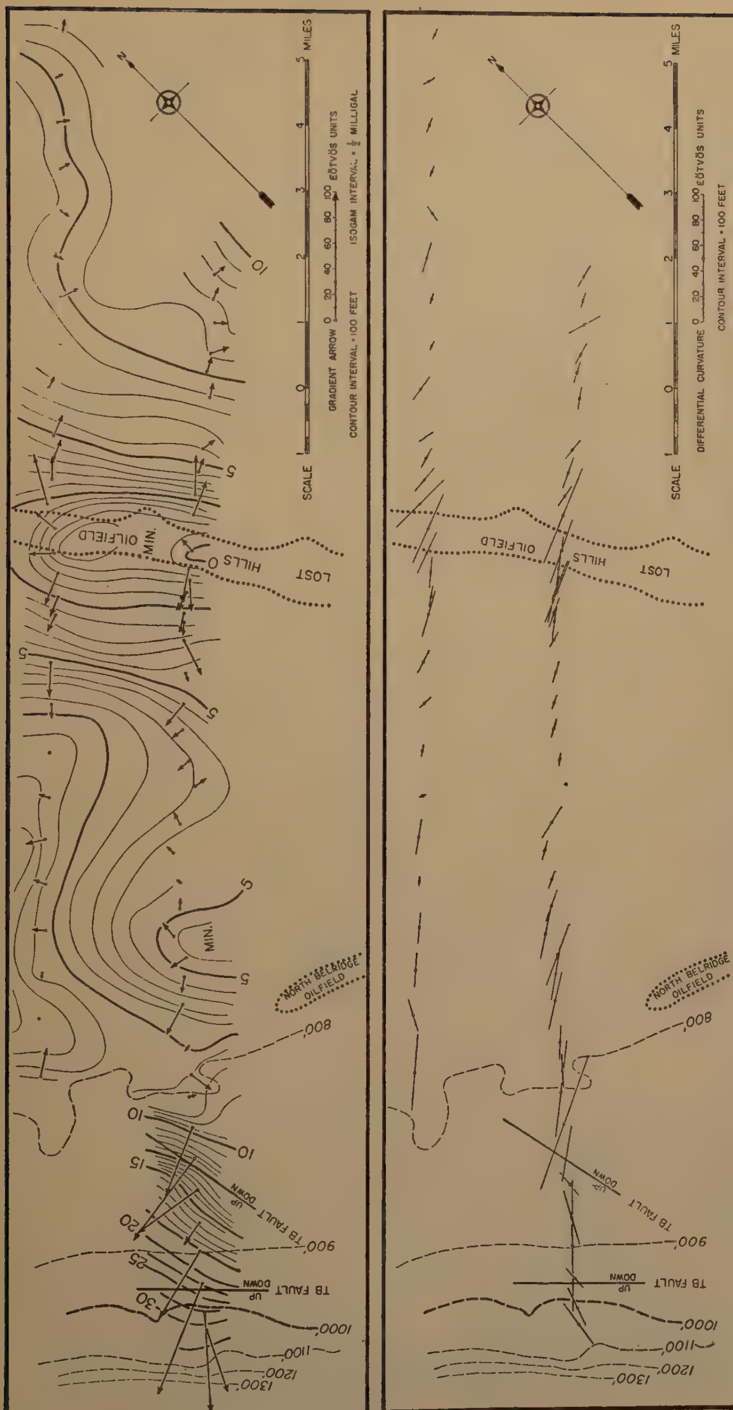

FIG. 1.—MAP OF TORSION BALANCE SURVEY OF LOST HILLS AREA, SAN JOAQUIN VALLEY, CALIFORNIA.
A. Gradient arrow-isogam map.
B. Differential curvature map.

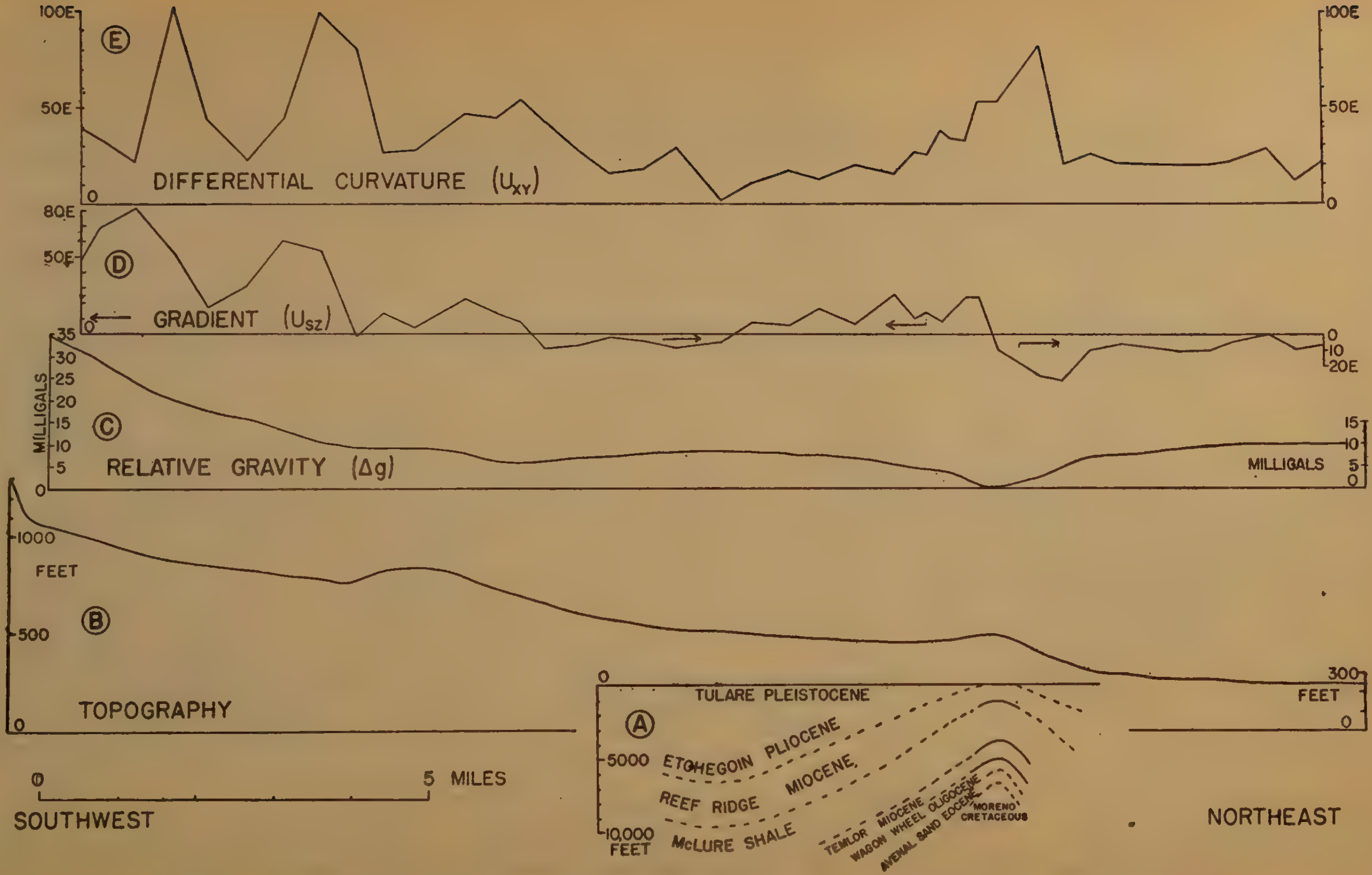

FIG. 2.—PROFILES SOUTHWEST-NORTHEAST ACROSS LOST HILLS AREA, SAN JOAQUIN VALLEY, CALIFORNIA.
A. Structural section across Lost Hills anticline (partly from geologic and partly from reflection seismic data).
B. Topographic profile. *C*. Profile of relative anomalous gravity. *D*. Profile of Eötvös gradient. *E*. Profile of differential curvature.
Profiles are along southeastern end of torsion balance traverses of Fig. 1. Structural section, strictly, lies slightly southeast of that traverse line.

is large in the southwestern third of the area of the survey and small in the northeastern two thirds. An east-west to east northeast-west southwest regional differential curvature transverse to the trough should be produced by a trough such as the San Joaquin structural trough, filled with relatively lighter sediments in heavier sediments; and in a relatively flat-bottomed trough it should be large near and in front of the edge of the valley. The topographic San Joaquin Valley should also produce regional differential curvature oriented transverse to the valley and increasing in amplitude near the middle of the valley.

Lost Hills Minimum and Anticline

A sharp gravity minimum marks the sharp Lost Hills anticline. The two coincide closely in general position but the crest of the minimum lies ⅙ mile southwest of the crest of the anticline, as indicated by the zone of production. Allowance for any southwesterly regional gradient would shift the true position of the Lost Hill minimum slightly farther to the southwest. The Lost Hills anticline is indicated by the reflection seismograph to be asymmetric with a steeper flank on the northeast than on the southwest. This asymmetry and its direction are clearly indicated by both the gradient profile (Fig. 2*D*) and the differential curvature profile Fig. 2*E*, for both of the respective anomalies are sharper and more abrupt on the northeast than they are on the southwest. The divergence between the position of the crest of the gravity anomaly and the crest of the structure also is in agreement with that asymmetry, for on an asymmetric anticline the crest of the gravity anomaly should be shifted slightly down the gentler flank from the structural crest.

The causative geologic feature producing the Lost Hills minimum would seem to be the thickening of the diatomaceous-siliceous McLure shale and of the base of the Reef Ridge formation in the core of the Lost Hills anticline. The distance between the positions of the opposing maximum gradients is approximately twice the depth to the causative mass; the depth to the abnormally light mass that is producing the Lost Hills minimum, therefore, is approximately ½ mile. The Reef Ridge formation includes diatomaceous shales in its lower part and much of the McLure shale is siliceous. The diatomaceous-siliceous shales of California commonly are abnormally light rocks. The depth of ½ mile on the axis of the anticline lies approximately in the center of the McLure shale. The abnormally light diatomaceous shale would seem definitely to be the cause of the Lost Hills anticlinal minimum and of the other anticlinal minimum of that general area. No thickening of the beds in the core of the Lost Hills anticline is suggested by the geologic or seismic reflection data. Simple anticlinal arching of the beds would not seem to be competent to produce so simple and so sharp an anomaly as the Lost Hills minimum. The gravity data seem strongly to suggest axial thickening of the diatomaceous shales.*

Northwest of North Belridge Minimum.—The plunging northwest end of another definite minimum similar to the Lost Hills minimum was mapped 6 miles southwest of the latter. This minimum is not as sharp as the Lost Hills minimum. The southeastern line of the profile passes a few miles northwest of the North Belridge oil

* NOTE by C. A. HEILAND.—The Lost Hills field seems to be characterized not only by a low in gravity but magnetism as well. This may be inferred from E. D. Lynton's article [*Bull.* Amer. Assn. Petr. Geol. (Nov. 1931) 15, 1369] describing the magnetic anomalies extending from the Kettleman Hills structure southwest to the north end of the Lost Hills field. The cause of the magnetic low is, however, different from that of the gravity low. There occur, in the upper part of the Etchegoin, some highly magnetic vivianitic sandstones that probably have been eroded from the top of the structure. The buried suboutcrops of these magnetic beds can be traced completely around the South dome of Kettleman Hills, including the Lost Hills field. The magnetic susceptibility of these sandstones is high—of the order of 4000×10^{-6} c.g.s.

field. This minimum lies approximately northwest of the field and would seem presumably to reflect the dying out of the northern end of the Belridge-North Belridge line of folding. The trend of the North Belridge field, however, is west-northwest. But at the intersection of the prolongation of that axis with the southeastern line of profile, the gravity data give no indication of structure.

Synclinal Maximum between Lost Hills and North Belridge Anticlines.—A broad, plunging maximum was mapped between the North Belridge minimum and the Lost Hills minimum. It would seem to reflect the broad syncline that lies between the Lost Hills anticline and the Belridge line of folding. The axis of the maximum lies only 1500 ft. east of the axis of the syncline according to the seismic data on which that part of the structure profile of Fig. 2*A* was based.

Interpretation of Anticlinal vs. Synclinal Character of Anomalies from Their Form

The respective forms of the gradient and differential-curvature anomalies above Lost Hills and above the syncline to the southwest are sufficient in themselves to show that the Lost Hills structure is sharp, peaked and convex upward, and that the syncline is flat-topped. This conclusion arises from the following theoretical considerations:*

If the causative mass has a triangular cross section with base down, the positions of opposing numerical maximum gradient are relatively close together compared with the general width of the anomaly, and the crest of the gravity anomaly is sharp while the differential curvature is at a numerical maximum at the point of the gradient reversal. But if the prism is tabular in cross section and lies on its base, or if it is triangular and lies on its apex, the positions of opposing numerical gradient maxima will be relatively far apart, the gravity anomaly will be rather flat-topped and the differential curvature will be small or average at the point of gradient reversal. The respective forms of the gradient and differential-curvature profiles are independent of the sign of the specific gravity of the causative mass since a change of sign of the specific gravity contrast merely rotates the gradient arrows through 180° and the *R* lines through 90° without changing their position or magnitude.

The Lost Hills gravity anomaly, therefore, indicates definitely that it is produced by an anticline while the maximum to the southwest indicates that it is produced by a syncline, or trough, or horizontal tabular body.

The form of the northwest of North Belridge minimum does not indicate clearly whether the causative structure is an anticline or a syncline. The maxima on the gradient and differential-curvature profiles are not clearly defined, and the observed anomaly cannot be clearly assigned in either of these two categories of anomalies, for on the basis of the form of the anomaly alone, the causative mass cannot be determined as anticlinal or synclinal. Unless the density relations in the subsurface were known to the geophysicist, he would have to base his interpretation on the general principle that increase of specific gravity with depth is commoner than the reverse, and therefore he would interpret the anomaly as a sharp syncline; or, if he were wise, he would run a more detailed profile farther to the south, and the form of the anomaly there might, or might not, be definite enough to show the anticlinal character of the minimum. With knowledge of the form of the Lost Hills minimum, but with or without knowledge

* The discussion that follows and the unique solution obtained by Barton are based implicitly upon the assumption of a known shape for the causative mass and relatively close proximity to the surface.—Ed.

of their geology, the geophysicist would be justified in the interpretation of the northwest of North Belridge minimum, by analogy, as anticlinal.

But analogies do not always hold, and if a geophysicist attempted to carry this particular type of interpretation by analogy far away from the southwestern part of San Joaquin Valley, or apply it to all anomalies within the southwestern part of the San Joaquin Valley, he would get into serious difficulties.

Gravity Minimum at Tepetate on Very Deep Salt Dome, Acadia Parish, Louisiana

By Donald C. Barton

Tepetate affords examples: (1) of a salt-dome minimum badly obscured by a regional trough of minimum; and (2) of uplift so slight in the producing horizon that the regional gulfward dip of the beds has shifted the structural crest one mile updip from the center of the minimum.

The Tepetate oil field lies mainly in sec. 29 T.7S. R.2W., Acadia Parish, Louisiana. The structural crest in the main productive horizon (Marginulina zone, Oligocene), at 8240 ft., lies north of the center of the section. The Tepetate minimum is central in sec. 34. The discovery of the field is to be credited to the torsion balance and reflection seismograph. The torsion balance survey was made in 1929. The seismic reflection surveys were made in 1933 and 1934. The discovery well was completed in August 1936. The production to July 1, 1937 has been approximately 2,600,000 barrels.

Relation of Tepetate Minimum to Regional Anomaly

The regional framework of anomalous* gravity of southwestern Louisiana consists of a large east-west trough of minimum. The trough line of the minimum in general is parallel to the main line of the Southern Pacific lines from Lafayette to Vinton, and lies a few miles north of it. Large secondary minima, probably coalescent salt-dome minima, are superimposed on the regional trough of minimum. But in general the intensity of anomalous gravity increases at a fairly regular rate southward from the trough line at least to the Gulf shore. The amplitude of the increase from the trough line in the vicinity of the Tepetate minimum to the southernmost area, covered by the torsion balance, south of Pecan Island, in southern Vermilion Parish, is 32 milligals. Northwestward the intensity of gravity increases 36 milligals over a distance of 40 miles to a crest of maximum that runs from central western Beauregard Parish east-northeastward.

The north-south transverse profile of relative anomalous gravity across this regional trough of minimum and the superimposed Tepetate minimum is given in Fig. 1*A*.

The Tepetate minimum lies very slightly north of the trough line of the east-west regional minimum and is badly obscured by that minimum (see Fig. 1*A* and Fig. 2). It is obscured further by the presence of

Gravity data published by permission of Mordelo Vincent (Jr.); stratigraphic and structural data published by permission of Humble Oil and Refining Co. Paper was written in July 1937.

* This anomalous gravity is relative gravity calculated from the gradient values $\frac{\partial^2 U}{\partial s\, \partial z}$ of torsion balance surveys. It essentially is relative gravity reduced to any potential surface between sea level and 200 ft. elevation, corrected for the variation of gravity with latitude, for local topographic effects, and approximately for regional topographic effects. It corresponds approximately to the relative Bouguer anomalous gravity except that the correction for the regional topography is slightly more accurate than that made in the simple Bouguer correction.

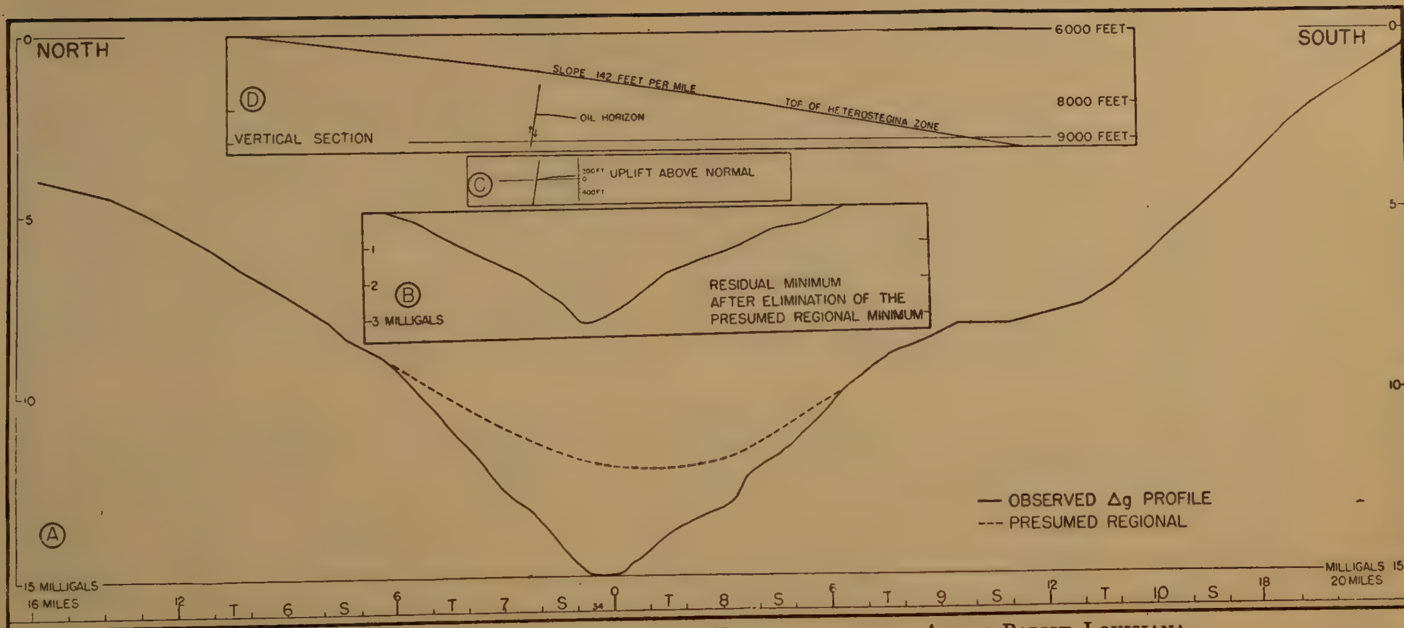

FIG. 1.—NORTH-SOUTH PROFILES THROUGH THE TEPETATE OIL FIELD, ACADIA PARISH, LOUISIANA.

A. Profile of anomalous gravity.
B. Profile of the Tepetate residual anomaly.
C. Profile of uplift in the oil sand.
D. Structural section showing: (1) regional slope on the top of the *Heterostegina* zone (Oligocene); and (2) the structure on the oil sand.

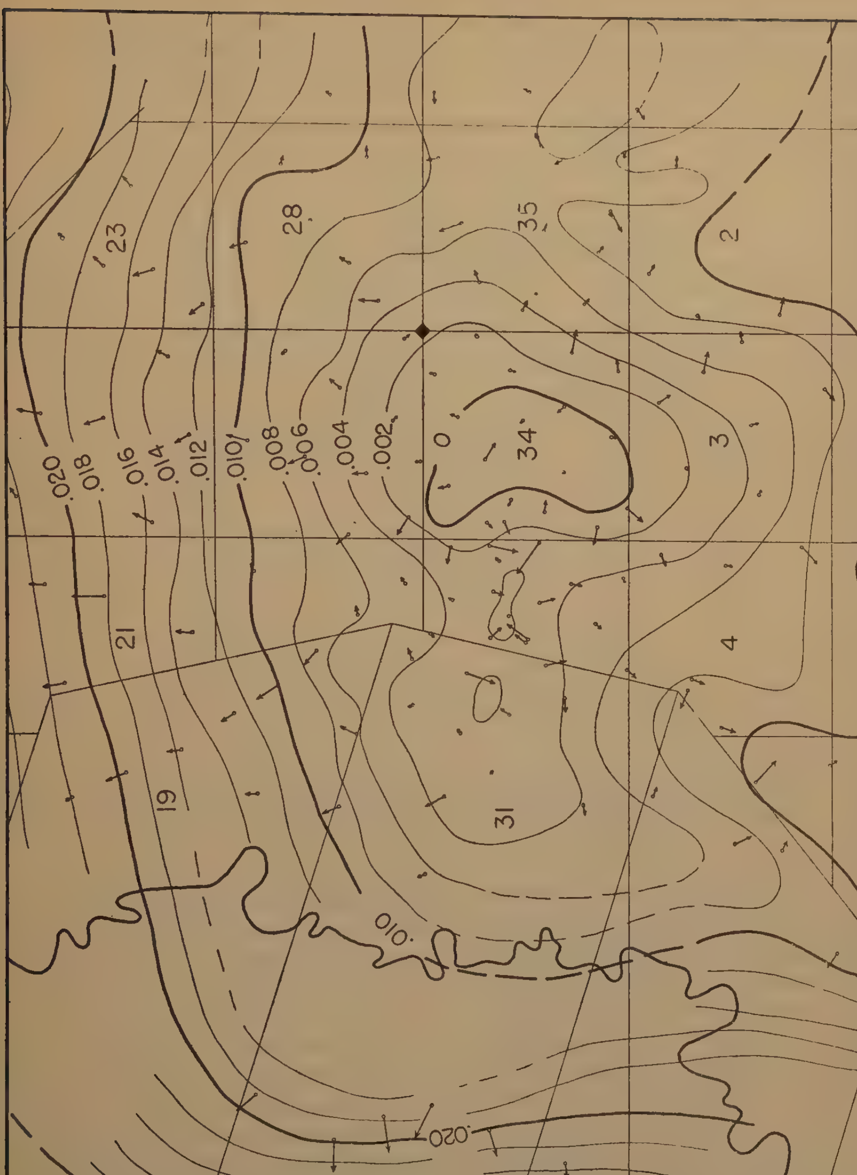

FIG. 2.—Gradient arrow and isogam map of part of the original torsion balance survey, Tepetate area.

what might be called a second-order minimum extending eastward from it, and by the presence of a less definite trough of minimum extending south-southwestward from its southwest edge. The survey was rather sketchy in those areas. The two latter anomalies may or may not be the effects of the minima of adjacent deep domes; the interpretation is not clear on the basis of the data. Although the Tepetate minimum is badly obscured, the presence of some such minimum central near sec. 34, T. 7 S., R. 2 W. can be recognized on the map of the observed anoma-

lous isogams (Fig. 2) and can be surmised strongly in the transverse Δg profile in Fig. 1*A*.

regional isogams, the residual isogams of Fig. 3 were obtained. These residual isogams represent the resultant anomaly of

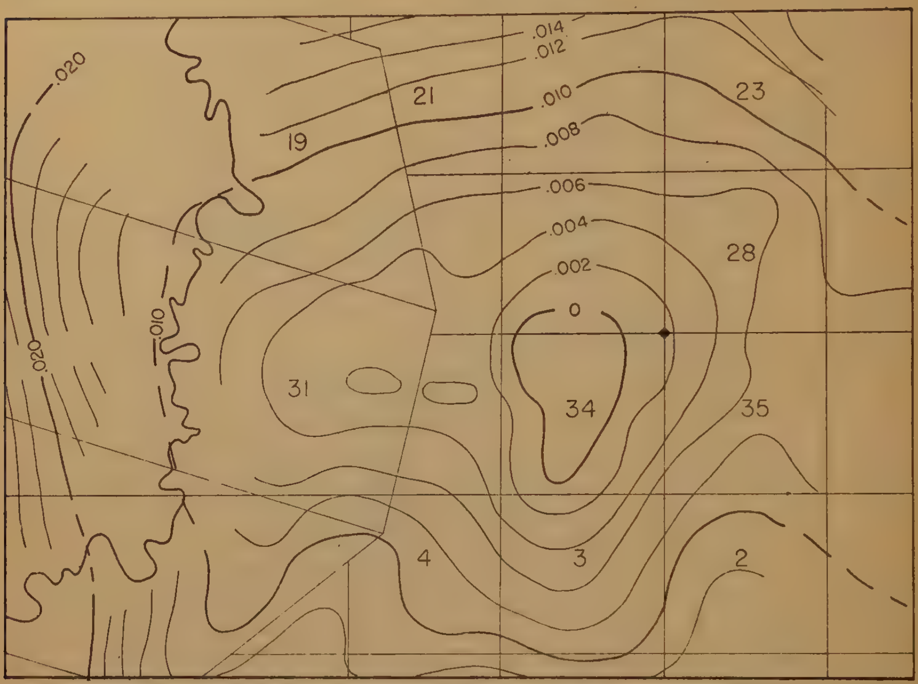

FIG. 3.—RESIDUAL ISOGAM MAP, TEPETATE AREA, AFTER ELIMINATION OF THE REGIONAL ANOMALY OF FIG. 1*A*.

The results of a study in the approximate elimination of the regional trough of minimum is shown in Fig. 1*B* and Fig. 3. The regional anomaly was obtained from the Δg profile of Fig. 1*A*. The assumption was made that the profile of regional Δg across the Tepetate minimum should be a smooth curve projecting, with lessening slope, the two flanks of the minimum. The dashed line of Fig. 1*A* was drawn by inspection as representing such a smoothly curving profile of regional Δg across the Tepetate minimum. The regional isogams were drawn as straight lines, parallel to the mean strike of the isogams of the north flank of the regional trough of minimum, and spaced according to the dashed curve of Fig. 1*A*. By subtraction of the assumed the Tepetate minimum and of the other nonregional anomalies.

GEOLOGIC STRUCTURE

The doming at Tepetate is faint down to as great depths as drilling has gone. The production comes from a sand in the Marginulina zone of the Middle Oligocene (regarded by many geologists as basal Miocene) at a depth of 8300 ft. The structure (Fig. 4) in the producing formation is a low, subcircular dome "closed" on the north by an east-west fault, downthrown on the south. The crest of the structure lies at a depth of 8235 ft. with the water table at a depth of 8320 ft. and a productive area that extends approximately 1¾ miles in an east-west direction

and 1¼ miles in a north-south direction. The structural relief east-west across the center of the oil field over the width of the productive area is only 130 feet.

minimum. Regional dip produces a shift of the structural crest updip from the position of maximum uplift in a bed. The regional dip on the top of the *Heterostegina*

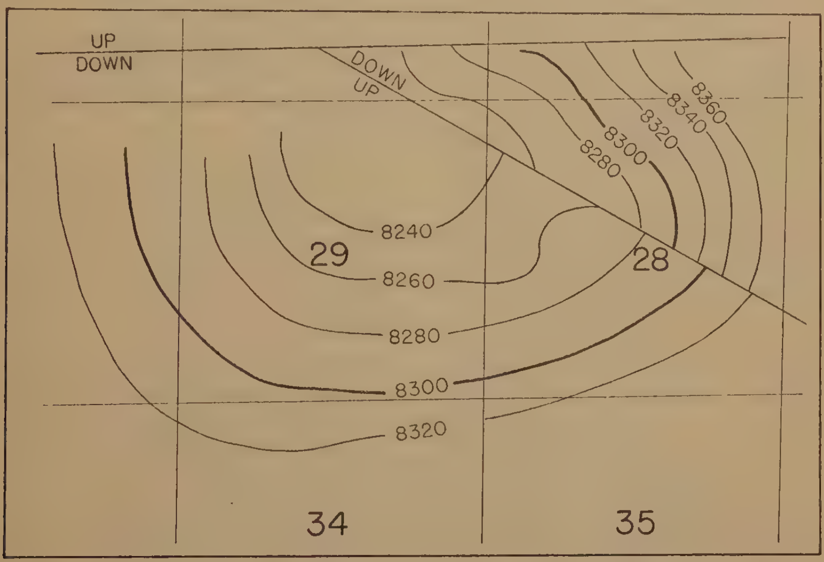

FIG. 4.—MAP OF STRUCTURE CONTOURS ON TOP OF THE OIL SAND, TEPETATE OIL FIELD.

zone in this general area is 142 ft. per mile, according to the regional structure-contour map of the Humble Oil and Refining Co. The lines of equal uplift at Tepetate (Fig. 5) were obtained by subtraction of that regional dip from the structure contours of Fig. 4. Since drilling has not extended far enough to the south and southeast, the center of uplift is not definitely located but would seem to lie near the center of the northeast quarter of sec. 34 T. 7 S., R. 2 W. Thus the centers of uplift and of the residual gravity minimum would appear to lie fairly near to each other. This is shown in Fig. 6 where the lines of equal uplift are superimposed on the residual isogams. The form of the uplift, as far as it is known, can be seen to conform fairly well with the form of the residual gravity minimum central in north central sec. 34.

SHIFT OF CENTERS OF GRAVITY MINIMUM, STRUCTURAL CLOSURE, AND UPLIFT

The centers of the structural crest and of the minimum are shifted slightly more than a mile from each other. The center of the observed Tepetate minimum is slightly south of the center of sec. 34 and the center of the residual minimum lies slightly north of the center of sec. 34. The structural center is slightly north of the center of sec. 29, the section to the north of sec. 34. Thus the centers of the structure and of the minimum are shifted a mile, or possibly slightly more, from each other.

The shift probably is geologic and not gravitational, and seems to arise from a shift of the structural crest caused by the regional dip. The position of maximum uplift does not coincide with the position of the structural crest but agrees more closely with the center of the residual

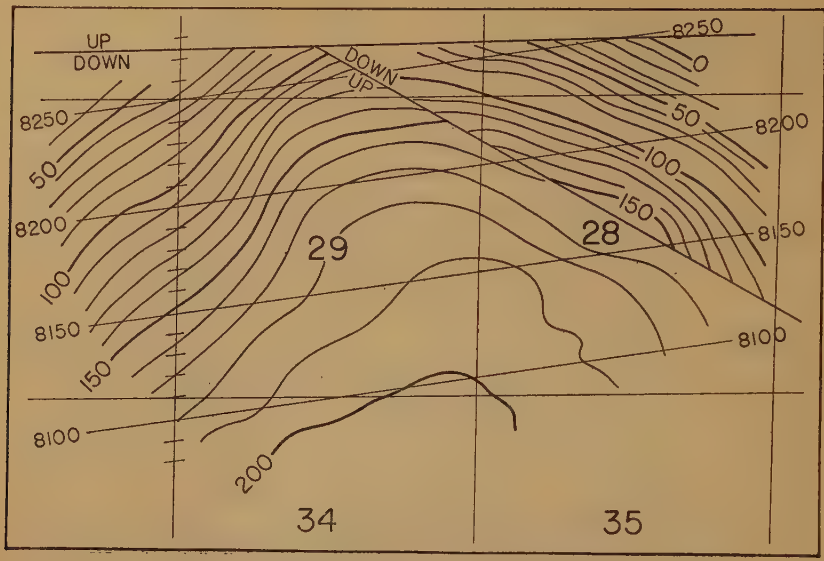

FIG. 5.—MAP OF UPLIFT ON THE OIL SAND, TEPETATE OIL FIELD.

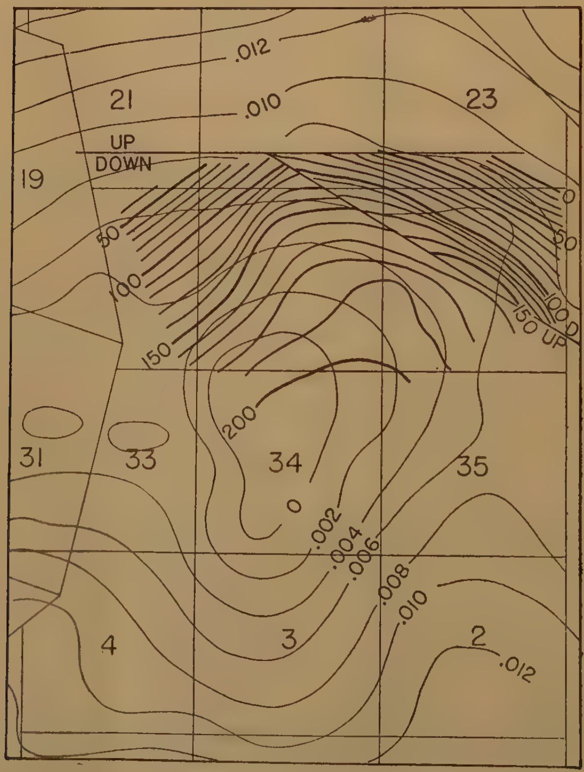

FIG. 6.—SUPERIMPOSITION OF LINES OF EQUAL UPLIFT ON THE RESIDUAL ISOGAMS, TEPETATE AREA.

Necessity of Periodic Reinterpretation

The history of Tepetate shows the necessity of a periodical re-evaluation of geophysical data. Knowledge of the significance of anomalies accumulates with the passage of time, and as the skill of the geophysicist in the interpretation of anomalies increases. Old interpretations, and the data on which they are based, should be re-examined periodically to determine whether something can be seen in the data that was not apparent earlier. The Tepetate minimum was mapped in 1929 by a torsion balance party working for the late Mordelo Vincent, of Eunice, Louisiana. I made an oral report in 1929 on that and other torsion balance surveys made for Mr. Vincent. No record of the report was kept, but presumably a recommendation was made that this minimum was too low grade a prospect for a small independent oil operator. Such a recommendation would have been in accordance with the thought and conditions of that time. The theoretical significance of minima such as those of Lost Lake, Edgerly, and Roanoke was known to geophysicists at that time, but those and all similar minima seemingly had been condemned by reasonably deep (for that day) dry holes well located near the respective centers of the anomalies. The tests at Roanoke and Lost Lake had gone to depths of 4000± ft. and at east Edgerly to 5200 ft. without shows of oil or gas and without indication of salt-dome materials or of uplift. Salt-dome minima rather generally, therefore, were regarded as condemned as the indicators of structure within reach of the drill; and even "textbook" examples of such minima had no commercial value.* Tepetate, however, is not even a "textbook" example, for it is badly obscured by the regional anomaly and the adjacent anomalies; and the technique of the elimination of regional anomalies and of the effects of adjacent salt-dome minima was poorly developed at that time. Reversal of opinion in regard to the commercial significance of minima came in 1929. The existence of the Lost Lake salt dome had been confirmed by the seismograph and the drill. The existence of the Edgerly salt dome had been confirmed by the drill. A good show of oil had been obtained at Roanoke. The Sugarland oil field had been found on a good minimum; and in the summer of 1929 the Esperson and Hankamer oil fields had been found on minima. By 1932, the importance of gravity minima was rather generally understood, and a fairly good minimum had come to be evaluated as commercially attractive.

The suggestion was made to Mr. Vincent that, although I had forgotten what his "big minimum" looked like, I believed that it was one of the type that had become valuable. After re-study of the data, the minimum was reported to be a "grade A torsion balance indication of a deep dome." A reflection survey was made late in 1933 and showed a vague structural nose. The survey now is known not to have been detailed enough to map such faint structure as Tepetate, particularly the peculiar type of structure there.

The prospect was shot by the Continental Oil Co. in 1934 and the structure delineated with reasonable accuracy, with the result that the first test was completed as a producer. Opinion in regard to structure of the type disclosed by the 1933 reflection survey has changed since that time. In 1933 and in 1934, neither the company that had made the survey or several other companies to which the data of the survey were submitted, regarded the apparent structure worthy of testing or even worthy of further reflection work. A similar structure today would be regarded as drillable, although it would not

* For a more detailed discussion of the history of the torsion balance in the Gulf Coast, see D. C. Barton: Review of Geophysical Prospecting for Petroleum. *Bull.* Amer. Assn. Petr. Geol. (1930) 14 (9), 1105–1127.

be considered a first class prospect, but a more detailed reflection survey than that made in 1933 would be made by a conservative company before drilling.

Verification of Predictions

The predictions made in 1932 from the torsion balance survey of Fig. 2, and in advance of the first reflection survey, were correct in regard to the existence of a deep salt dome but were incorrect in respect to the depth of the salt. They were also incorrect in regard to the position of the structure in beds down to a depth of 9000+ ft., but would seem to be approximately correct in regard to the position of the salt core. Those predictions stated that the minimum is "a grade A torsion balance indication of a deep dome"; that "it is difficult or impossible to tell whether there is doming within reach of the drill, but that the chance of the salt coming within 8000 ft. of the surface is better than 50–50." The center of the dome was placed slightly north of the center of sec. 34, but the minimum area recommended for blocking more than covered the present productive area.

Quantitative Calculations of Geologic Structure from Gravimetric Data

By Donald C. Barton

Calculations from the results of a torsion balance survey may give valuable information in regard to the parameters of a geologic body that is producing an anomaly. The form of the mass must be rather simple geometrically; it must be appreciably different in specific gravity from the surrounding medium, and both it and the surrounding medium must be homogeneous in specific gravity or their specific gravities must vary according to some simple known law. The observed anomaly must not be complicated by the overlapping anomalies of other features, although the presence of a simple regional gradient is not necessarily prejudicial to such calculations.

Calculations in Regard to the Cap of the Gulf Coast Salt Domes

Calculations of the depth, thickness and position of the edge of the cap rock of the salt domes in the Gulf Coast have proved to be of considerable value to the sulphur companies.

The cap rock of the Gulf Coast salt domes is usually a disk-shaped or thimble-shaped mass of rock that caps the crest of the salt cores and ranges in thickness from nothing at all to 1000 ft. The upper sixth of the cap rather commonly is a porous limerock. The next lower sixth or third of the cap commonly is composed of gypsum, which grades downward into anhydrite. The lower two thirds or half of the cap is composed of massive anhydrite. The commercial deposits of sulphur are found in the limerock and to a lesser extent in the gypsum and occur only on domes which have much limerock in the cap—a condition in the coastal domes which occurs only on domes on which a thick cap is present. Commercial deposits of sulphur do not occur on all domes which have much limerock in the cap.

Direct determination of the presence or absence of sulphur in commercial quantities is impossible except by the drill. But indirectly, by showing the absence of much cap rock, the torsion balance method can indicate the absence of sulphur, or, by showing the presence of much cap rock, it can indicate that sulphur may be present, and by delimiting the area of the cap rock,

Paper was written in July 1937.

can delimit the area in which prospecting by the drill is worth while.

Surveys of this type and the calculations from them have been made under the writer's direction for the sulphur companies on eight of the Gulf Coast salt domes.

Dome A

On dome A, cap rock was known to be absent over the crest of the dome. The first problem for the torsion balance survey was to determine whether or not any considerable mass of cap rock was present around the edge of the dome. The second problem would have been to delimit the cap rock, but the calculations from the results of the preliminary profiles failed to show the presence of cap rock. The sulphur company, therefore, drilled no prospect wells, and there has been no other drilling to check the predictions from these calculations.

Dome B

On dome B, the crest of the dome had been well prospected for sulphur. The problem left to the torsion balance survey was to delimit the extension of the cap beyond the limits of drilling. The drilling since the completion of the survey has been insufficient to check the accuracy of the predictions from these calculations.

Bryan Mound

On the Bryan Mound salt dome the problem was to find small extensions of the cap rock on the flanks of the dome. The sulphur was approaching exhaustion although the dome had been rather thoroughly drilled and, in general, the position of the edge of the cap rock seemed to be indicated fairly well by the wells into the cap and by a few wells that were off its edge. Wells had been drilled as close to the edge of the cap as drilling data seem to justify. The dome is approximately one mile in diameter, or 16,000 ft. in circumference. Thirty prospect wells would have been required to determine the presence or absence of small extensions of the cap rock here and there around the dome, beyond the postulated edge of the cap. The chance would have been good that many, or perhaps all of them, would have been a little too far out and have missed the edge of the cap. The purpose of the quantitative torsion balance survey, therefore, was to indicate areas of possible extension of the cap rock in order to reduce the number of prospect wells necessary to reduce the risk that a prospect well would not encounter cap rock, and to increase the chance that the first new prospect wells would find sulphur.

The problem can be visualized from Fig. 1. The main mass of the cap lay between depths of 750 and 1025 ft. The position of the top of the cap was known from hundreds of wells. The depth to contact of the cap with the underlying salt was known from a few wells but showed very slight variation. The specific problem was to determine the presence or absence of small masses of cap rock lying between the depths of 1200 and 2000 ft. that might produce maximum gradient effects of 1.5 to 2.5 E.

The field survey consisted of many radial profiles. The station interval was 300 ft. over the edge of the dome and 500 ft. on top, and on the outer ends of the profiles.

The terrane, in the main, was ideal, although the outer ends of the profiles were on salt marsh. Water reservoirs interfered at critical places on a few of the profiles.

A regional gradient of 8 $\pm$ E was present and was approximately of the same size as the maximum gradient produced by the cap rock. Although the area of the field survey was not large enough for accurate determination of the regional gradient, an approximate value was determined

and was subtracted graphically from the observed values of the gradient.

The type of the predictions that were made as the result of the calculations from the torsion balance data are shown in Fig. 1. No extension of the cap was found on some profiles, as, for example, on the profile of Fig. 1. Considerable extensions of the cap were found on other profiles and on still other profiles no extension, a moderate extension and a considerable extension seemed about equally likely. The calculations, technically, were unsatisfactory, for good fits of calculated to observed gradient profiles could not be obtained. The predictions in regard to the extensions of the cap were reported as having a probable accuracy of 40 per cent and as probably overestimating slightly rather than underestimating the extension of the cap rock.

The accuracy of the predictions was shown by the results of subsequent drilling to be approximately 80 per cent, according to the following note from the engineer in charge of the operations at the Bryan Mound mine:*

Prior to the torsion balance survey, the cap-rock area of the Bryan Mound salt dome was considered to be 690 acres. The torsion balance survey indicated a thickening of the cap-rock beyond points where previous drilling had shown it to thin out, principally on the east and south flanks of the dome, and a lesser extension on the west flank, indicating a total of 140 acres extension of the known dome area. Drilling results later confirmed existence of the cap-rock extensions as indicated by the torsion balance survey, the cap-rock extensions as proved by drilling actually totalling 112 acres. The depth of the cap-rock on the extensions ranged from 1100 to 1400 ft. and conformed closely to the predicted depths. The thickness of this cap-rock was predicted as ranging upward to 300 feet, and although this thickness was not definitely checked by drilling, which in sulphur mining is normally stopped on encountering anhydrite, the

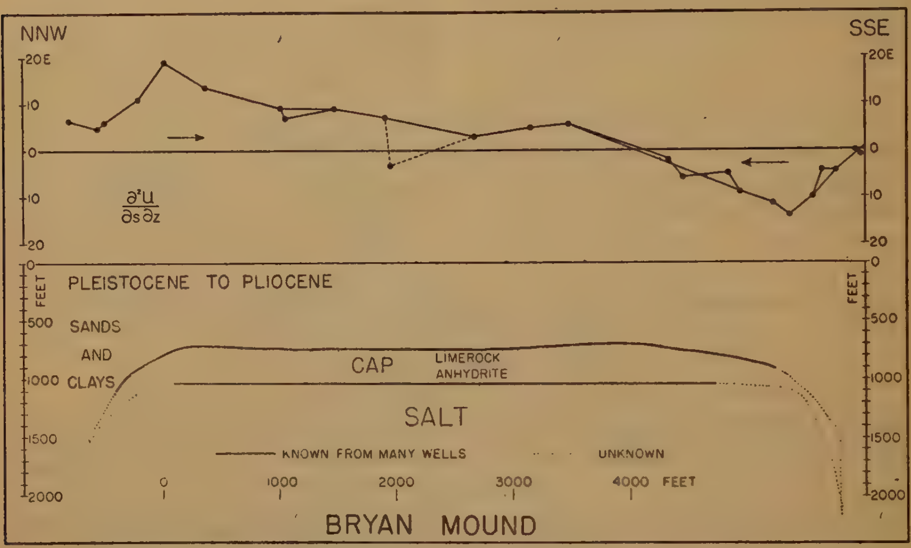

FIG. 1.—NORTH-NORTHWEST, SOUTH-SOUTHEAST STRUCTURE SECTION AND GRADIENT PROFILE ACROSS BRYAN HEIGHTS SALT DOME.

Solid line in structure section indicates "well known from drilling"; dotted line, "surmised from torsion balance calculations."

Data furnished through the courtesy of the Freeport Sulphur Company.

* E. H. McFarland, General Superintendent, Freeport Sulphur Co., Freeport, Texas, in letter to the writer Nov. 17, 1936.

limestone member of the cap-rock was frequently found to be as much as 200 feet in thickness.

In summarization, it may be stated that the torsion balance predictions as concerning cap-rock area, depth, and thickness were confirmed by drilling as being surprisingly accurate.

Equally high accuracy should not be expected in general in similar problems elsewhere. Part of the accuracy of the predictions presumably was accidental. A further part of the accuracy presumably was the effect of: (1) the absence of serious variation of density within the beds surrounding and covering the cap, and (2) the favorability of the terrane for good observation with the torsion balance.

Part of the technique of this survey is now regarded by the writer as rather crude for work intended for the detection of masses whose maximum gradient effect may be only 1.5 E. The station interval of 300 ft. in the zone of the edge of the cap and 500 ft. in the area of the center of the dome and on the outer ends of the profiles is too great. More stations are needed to give a better statistical value in smoothing gradient profiles. The Bryan Mound survey was the second one of these surveys made by the writer, and, as the result of his further experience, for a similar project he would use a 100-ft. interval in the zone near the edge of the cap, a 250-ft. interval in the area of the center of the dome, and an interval of 250 to 400 ft. on the outer ends of the profiles.

Of the stations near the edge of the cap, two 180° stations would be used between two full stations; that is, both components of the gradient would be measured at every third station, but at the two intermediate stations only the radial component of the gradient would be measured. In the calculations on the Bryan Mound survey the comparison of the calculated and observed values was done graphically. Use of the method of least mean square difference would be more accurate in handling the small differences between the observed and the calculated gradient values.

Hoskins Mound

The survey of the Hoskins Mound salt dome was the first of this type made under the writer's direction, and its results were the most spectacularly successful of all the surveys, but the task was the simpler and the terrane the more favorable.

The purpose of the survey was to delimit the extension of the cap rock at the partially known Hoskins Mound salt dome. The status of knowledge of the dome at the time of the survey is shown in Fig. 2. The central part of the dome was known from scattered prospect wells, most of them old. Mining of sulphur was being carried on over the southwest quadrant of the flank of the dome. The edge of the cap was surmised to lie inside the centers of quadrangles 4F, 3F, the center of the NE. ¼ of 2E and the north line of 2D. That surmise was based partly on the data of Fig. 2 and partly on the position of the edge of the topographic mound. The Freeport Sulphur Co. wished to block out the extent of its ore reserves with a minimum of expenditure and wished to know whether any considerable mass of cap rock extended beyond those limits and, if so, how far, at what depth, and in what thickness.

Hoskins Mound is an average shallow Gulf Coast salt dome. Its diameter is one mile. The depth to the crest of its cap rock is slightly less than 700 ft. The thickness of its cap is 500 to 600 ft. Hoskins Mound lies in the area in which the Beaumont prairie is merging into coastal marshy prairie. The terrane was excellent for observation with the torsion balance.

The technical task presented was the rather simple mapping of fairly large masses of cap at moderate depth in an area of good terrane.

FIG. 2.—STATUS OF HOSKINS MOUND SALT DOME AT TIME OF TORSION BALANCE SURVEY IN THE SPRING OF 1926.

Shows wells that had been drilled and structure contours on top of cap according to data from those wells.

Figures on Hoskins Mound published by permission of the Freeport Sulphur Company.

The field survey consisted of 13 radial profiles with an interval between stations of 500 to 600 ft. (see Fig. 3).

Confirmation of Predictions

The degree of agreement of the calculated depths with the corresponding depths to the top of the cap from subsequent drilling can be seen from the cross sections of Fig. 4. Statistically, the degree of agreement between the respective calculated depths to the depths from drilling is as follows:

Deviation of the calculated depth from drilling depth is:

- Less than ± 10 per cent: 49 per cent of the wells on the profiles.
- Less than ± 6 per cent: 32 per cent
- Greater than 30 per cent: 8 per cent

Mean of ratio $\dfrac{\text{drill depth}}{\text{calculated depth}}$ 1.11

Standard deviation................ ± 0.15

"Probable error"................. ± 0.10

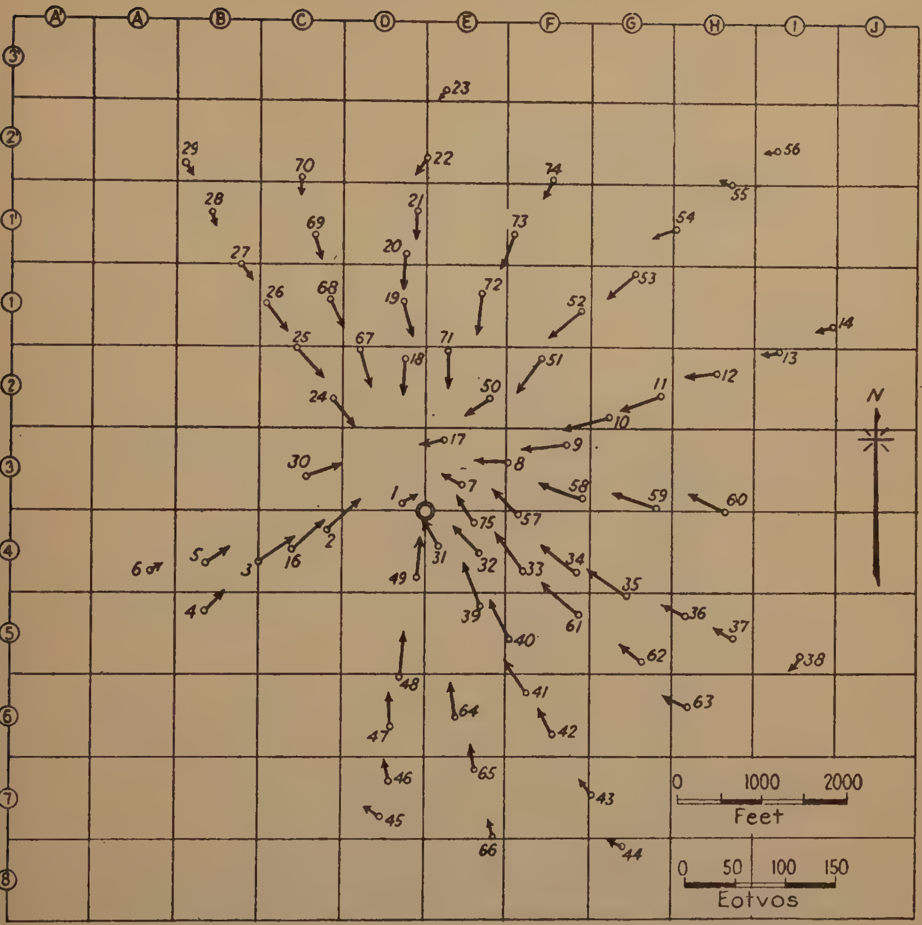

FIG. 3.—GRADIENT-ARROW MAP OF TORSION BALANCE SURVEY OF HOSKINS MOUND SALT DOME.

Variation of mean of ratio $\frac{\text{drill depth}}{\text{calculated depth}}$:

Above 600 ft.	0.93
Between 600 and 950 ft.	1.07
Between 950 and 1200 ft.	1.16
Below 1200 ft.	1.10
NE. profile	1.13
E.-NE. profile	1.17
E.-W. profile	1.31
N.-S. profile	1.03
NNW.-SSE. profile	1.16
NW.-SE. profile	1.04

Part of the deviation of the calculated depth from the drill depth is to be charged against the latter. The engineers of the Freeport Sulphur Co. have told the writer that well surveys show considerable deviation from the vertical in the wells more than a few years old. The wells that have been drilled during the past few years have been kept vertical. The apparent depth to the top of the cap in the older wells, therefore, will tend to be too great; and the ratio of drill depth to calculated depth will tend to exceed 1.00. But the general tendency for that ratio to exceed 1.00 is only partly attributable to that fact. It is the effect also of inaccuracy in the assumed relative specific gravity. The well depth, furthermore, is not a mean depth; but the calculated depth is the depth to a

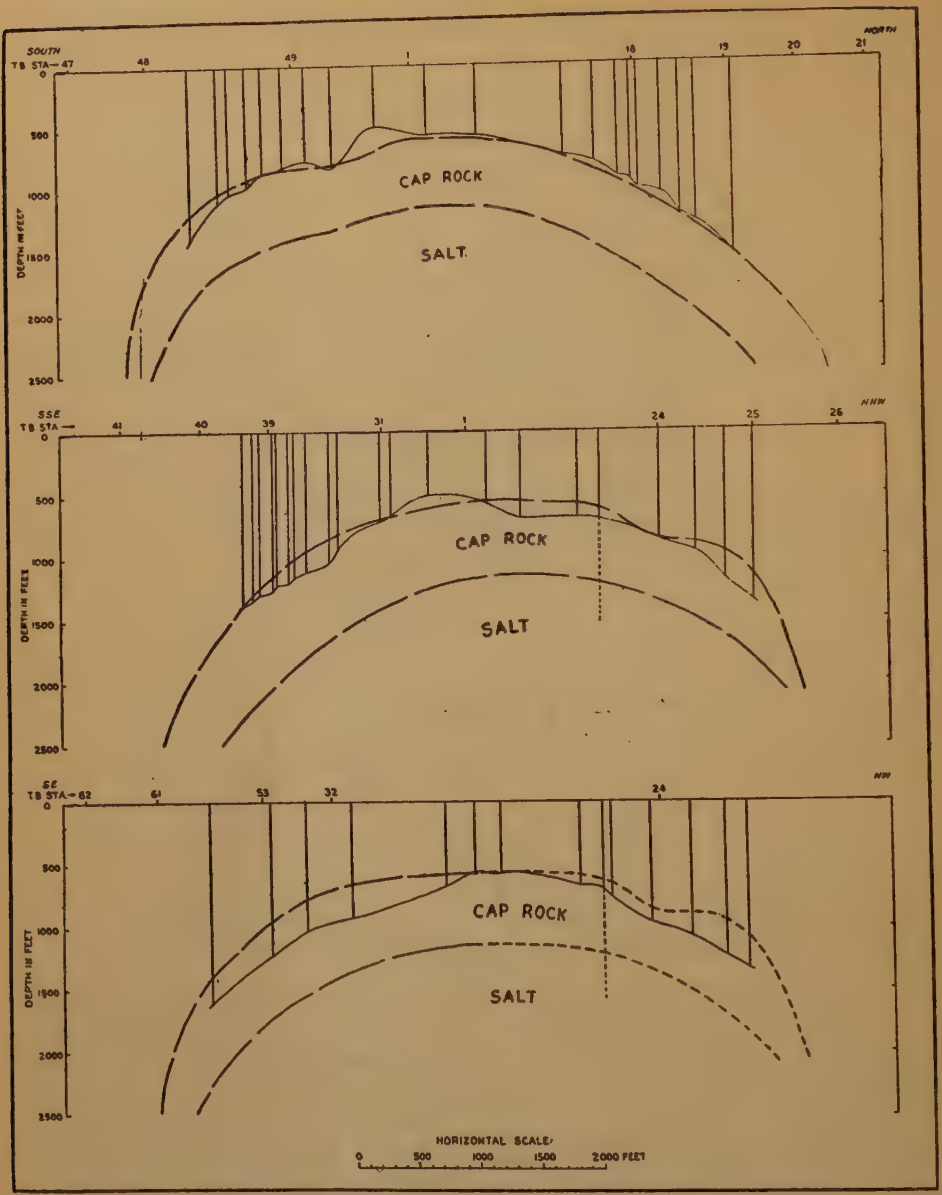

FIG. 4.—STRUCTURAL SECTIONS SHOWING COMPARISON OF CALCULATED PROFILE OF TOP OF CAP WITH PROFILE FROM WELL DATA.

Calculated profile is shown by heavy dashed line and profile from well data by lighter solid line. Wells on which latter profile is based are shown. The profile on the northwest, shown by short dashes, was based primarily on well data.

FIG. 5.—CROSS SECTIONS OF SOUTHWEST QUADRANT OF BELLE ISLE SALT DOME SHOWING PREDICTED TOP OF CAP AND SALT AND GRAPHIC LOGS OF SUBSEQUENT SULPHUR TEST WELLS.

smoothed-off surface of the cap. The wells of the east profile lie in a plunging trough in the surface of the cap. As their depth is greater than average to the cap in that sector, deviation of the calculated from the drill depth is extra large. The method seems to have given the depth to the top of the cap reliably within 30 per cent in all areas and on the whole to have given it within 15 per cent.

Belle Isle

The problem in the survey at Belle Isle salt dome, St. Mary Parish, Louisiana, was, first, to prove or disprove a geologically surmised extension of the dome approximately one mile beyond the known limits of the dome, and second, if the extension of the dome was proved, to map the depth, thickness, and limits of any considerable mass of cap rock which might be present.

The Belle Isle salt dome at the time of this survey was known to underlie Belle Isle, an island of dry land in the marsh, and was believed by many to be approximately coextensive with it (Fig. 5). The dome was surmised by other geologists to be much larger and to extend perhaps almost to the shore of Atchafalaya Bay. The Freeport Sulphur Co. made use of a quantitative torsion balance survey to

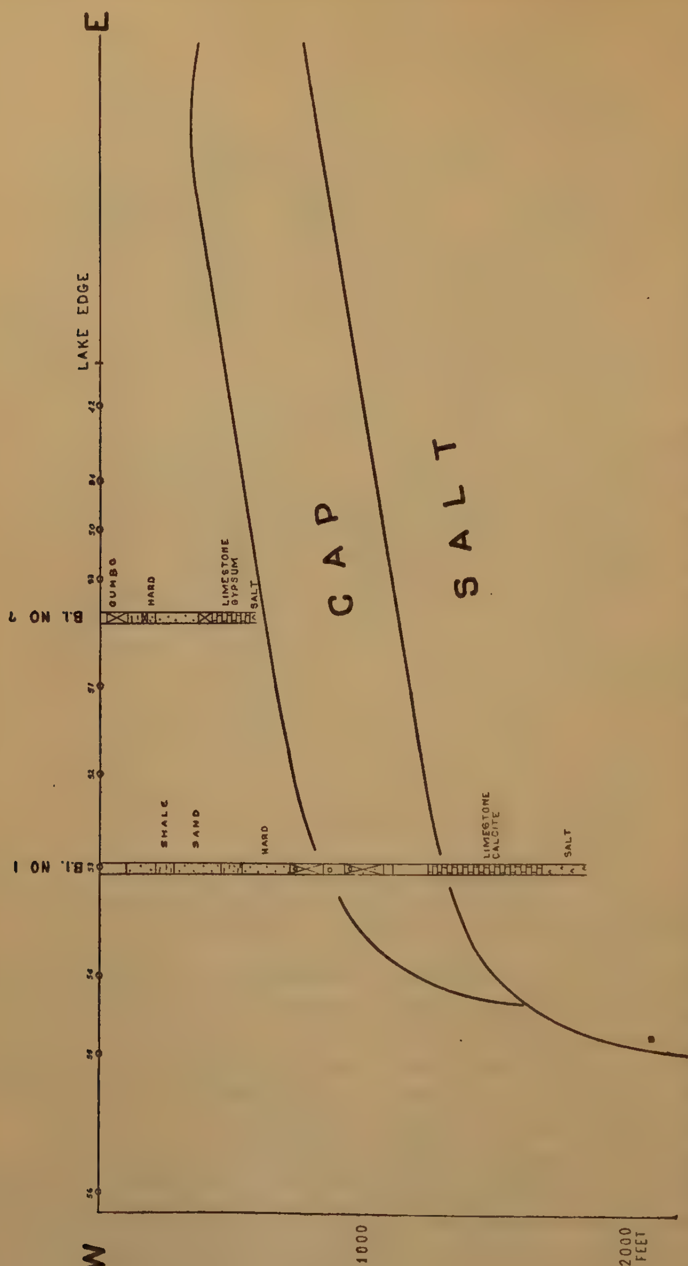

FIG. 6.—MAP OF BELLE ISLE SHOWING TORSION BALANCE SURVEY AND STATUS OF DOME AT TIME OF SURVEY, WINTER OF 1928–29. After Barton.[3] Data released through the courtesy of the Freeport Sulphur Company and the Belle Oil Corporation.

Continued on pages 47 and 48.

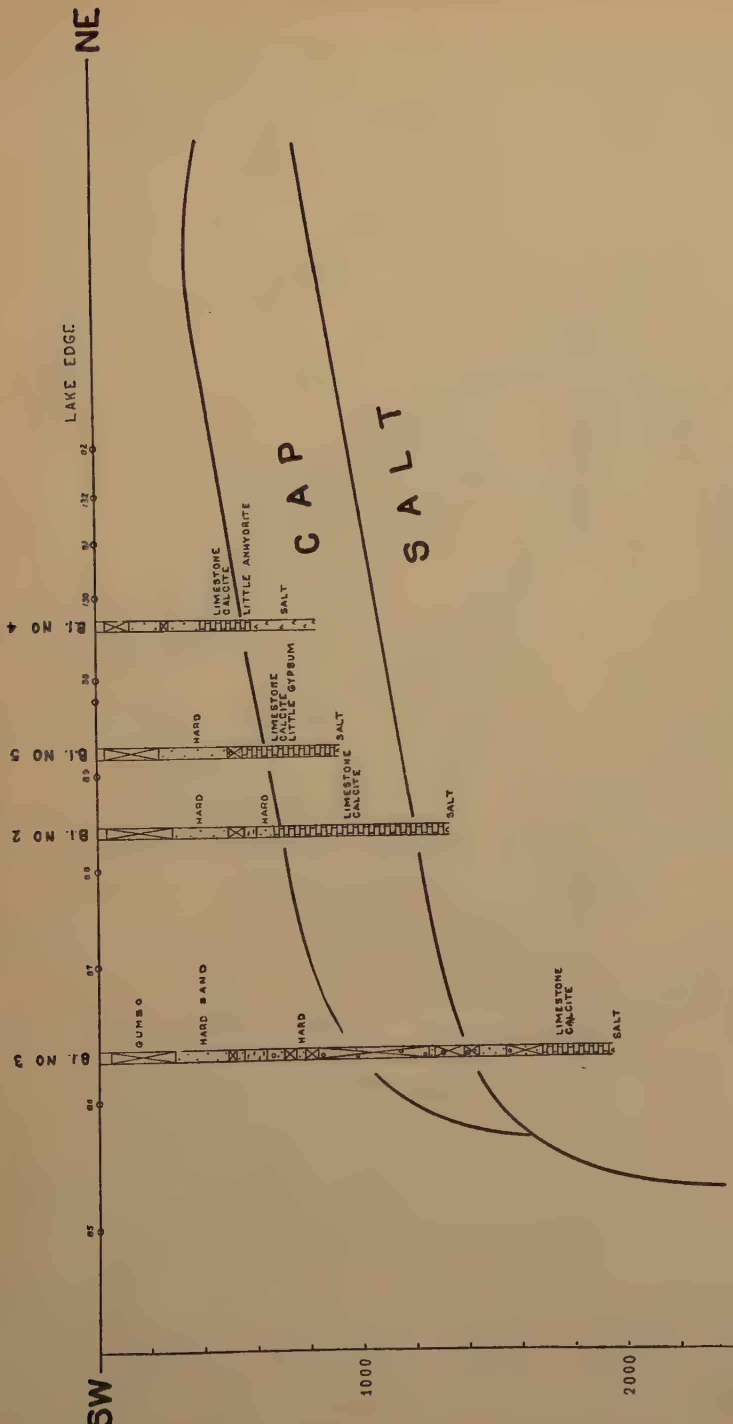

FIG. 6.—FOR DESCRIPTIVE LEGEND SEE PAGE 46.

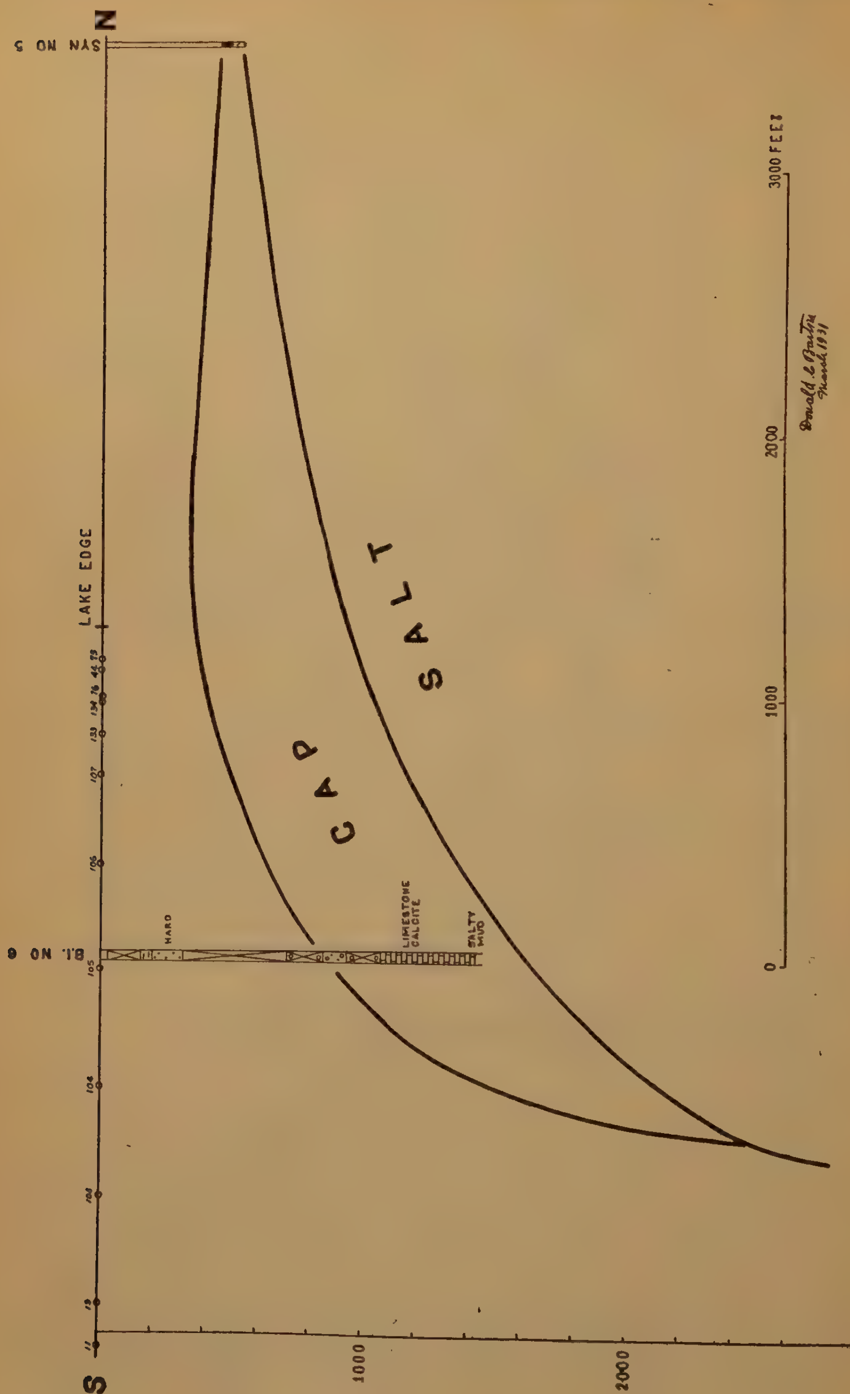

FIG. 6.—FOR DESCRIPTIVE LEGEND SEE PAGE 46.

confirm that surmise and to confirm the presence of a moderate thickness of cap over most of that extension of the dome. (Fig. 6.) the shore profile (Fig. 7) indicated that the dome extended southward beyond South Pond but did not reach the shore of the Bay.

FIG. 7.—STRUCTURE CONTOURS ON TOP OF CAP AS PREDICTED FROM CALCULATIONS VERSUS CONTOURS DETERMINED BY RESULTS OF DRILLING, BELLE ISLE SALT DOME.

A preliminary line of stations was run down the beach of the Atchafalaya Bay shore as the quickest and easiest method of checking the accuracy of that surmise. In good terrane for torsion balance work, a southerly radial profile would have been preferable, but in the actual situation at Belle Isle the beach provided easy going, whereas a radial profile would have involved fighting bad marsh. The degree of convergence of the observed gradient along

The radial profiles were then run. These profiles lay mainly across soft, soupy sea marsh covered by coarse, hummocky grass. The instrument was supported on 11-ft. lengths of 2-in. iron pipe, which were pushed down into the marsh and pulled up again by hand. No attempt was made to clean off the station site; and no station levels were taken or terrane correction used for stations on the marsh. A station interval of approximately 400 ft. was used.

Calculations then were made graphically to determine whether or not cap rock was present and to determine its depth, thickness, and extension, if present.

The subsequent drilling of seven prospect wells showed: (1) that the cap rock was present substantially as predicted, and (2) that quantitatively the predicted depths to the top of the cap were in error to the extent of 4 to 46 per cent with a numerical mean of 27 per cent, and (3) that the predicted thicknesses of the cap rock were in error to the extent of 6 to 63 per cent with a numerical mean of 42 per cent. The predicted cross sections of the cap rock on the three main profiles are shown in Fig. 6. The graphic logs in the same figure show the cap rock as it was found in the prospect wells. Quantitative data in regard to the degree of verification of the predictions of depth and thickness of the cap rock are given in Table 1.

readings, to take terrane levels and to make terrane corrections for the marsh stations; and, because of the high cost of observation in the marsh, it was not commercially practicable to reduce the resultant errors in the observations by decreasing the station interval. The specific gravities used in the calculations were based on shrewd guess and general experience. The calculated thickness of the cap, crudely, will vary inversely with postulated specific gravity.

Lake Washington

The problem of the survey on the Lake Washington (Grand Ecaille) salt dome, Plaquemine Parish, Louisiana, was to determine the possible presence of a major extension of the cap rock beyond the limits surmised from the scanty drilling. Oil was being produced from the cap rock; and the crest of the dome had been defined

TABLE 1.—*Verification of Predicted Depth and Thickness of the Cap Rock*
(Wells of Freeport Sulphur Company)

Well No.	Depth to Top of Cap, Ft.			Thickness of Cap, Ft.			Total Depth, Ft.	Character of Cap Rock
	Predicted	Actual	Error	Predicted	Actual	Error		
1	850	1,247	−397	470	442	+ 28	1,853	Hard lime rock with calcite veins, mostly impervious
2	690	660	+ 30	510	644	−134	1,321	Same as foregoing
3	1,180	1,672	−492	410	253	+157	1,940	Same as foregoing
4	550	393	+157	470	174	+296	828	Limestone and some gypsum and anhydrite
5	650	546	+104	500	327	+173	880	Same as foregoing
6	860	1,058	−198	740	387	+353	1,445	Broken lime rock and calcite; voids filled with sandy shale
7	620	426	+194	730	149	+581	580	Broken lime rock, calcite and gypsum; voids filled with sandy shale

Percentage errors in predicted depth to the top of the cap:
46, 4, 41, 28, 16, 23, 31 Numerical mean, 27 per cent
Percentage error in predicted thickness of the cap:
6, 26, 38, 63, 34, 47, 79 Numerical mean, 42 per cent

The error in the predictions in considerable part probably should be attributed to the marshy terrane and to slightly incorrect assumptions in regard to the specific gravity relations of the cap rock and the sediments. Because of the marshy terrane, it was impracticable to maintain normally rigorous limits of error in the

with approximate accuracy by the drilling. The position of the edge of the cap was defined by wells on the northwest and the east. A few other scattered wells into the salt or cap, or definitely missing the salt and cap, gave crude limits to the probable position of the edge of the cap. In order to avoid mutual interference with the oil

production, and to avoid excessive contamination of the sulphur by the oil, the Freeport Sulphur Co. wished to find, if approximately one mile. The depth to the top of the cap is 1130 ft. and the depth to the top of the salt is 1575 ft. The dome

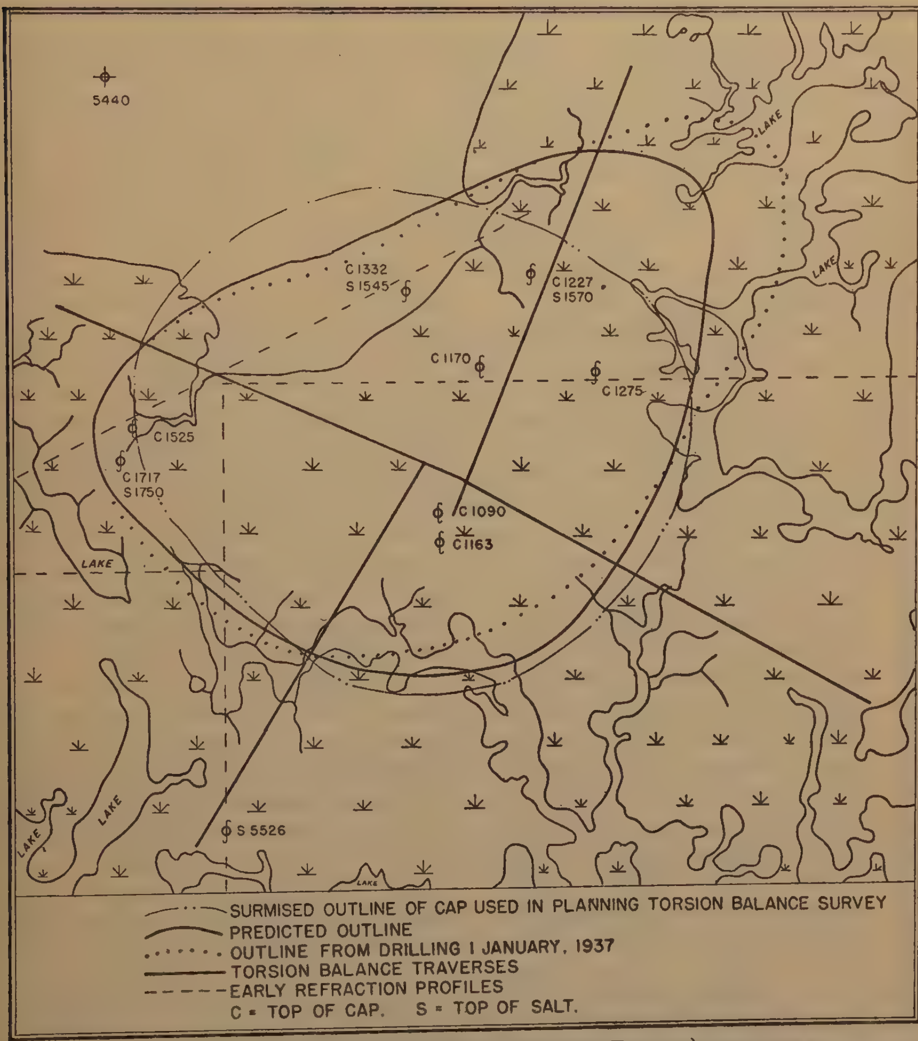

FIG. 8.—MAP OF LAKE WASHINGTON (GRANDE ECAILLE) SALT DOME.
Showing location of torsion balance profiles, terrane, outline of cap used in planning torsion balance profiles, wells of that date, lines of refraction seismic profiles, outline of cap predicted by calculations from data of torsion balance survey, corresponding structure contour drawn from well data on Jan. 1, 1937.

possible, major development of the cap rock below the level of the oil-water contact.

The Lake Washington dome is an average shallow Gulf Coast dome. Its diameter is lies in the area of bays and low coastal marsh along the edge of Barataria Bay.

The conditions were poor for a quantitative torsion balance survey. The best of the so-called land was soupy marsh

with a poor cover of grass. Wooden-lath fencing had to be laid out across the marsh to facilitate movement of the observers and equipment. A shallow bay impinging on the north edge of the dome, bayous, and spots of very bad marsh interfered with the location of profiles. A regional gradient of approximately 4 E is present in the area, and is approximately equal to the maximum gradient of the cap-rock anomaly. The survey could not be carried out far enough from the dome for even a fairly good determination of that regional gradient; and Lake Washington lay in the center of a large area in which no gravity surveys had been made. The regional gradient was handled in the calculation of the mean-square deviation of the calculated from the observed gradient profile. Several trial regional gradient profiles were assumed. When a trial-calculated gradient profile had been obtained, each of the assumed regional gradient profiles was added algebraically to it, and the mean-square deviation of the latter from the observed gradient profile was then calculated. The resultant having the least mean-square deviation was assumed to be the most probable and the trial section and the trial regional gradient profile combining to produce the least deviation were assumed to be the most probable section and the most probable regional gradient. This simultaneous handling of the regional gradient, of course, would have been much more difficult, and would have been weighted with the probability of lesser accuracy if the approximate size of the regional gradient had not been known, as well as the depth to the top of the cap and salt over the crest of the dome, the position of the northwest edge of the cap, and the depth and thickness of the cap at that edge.

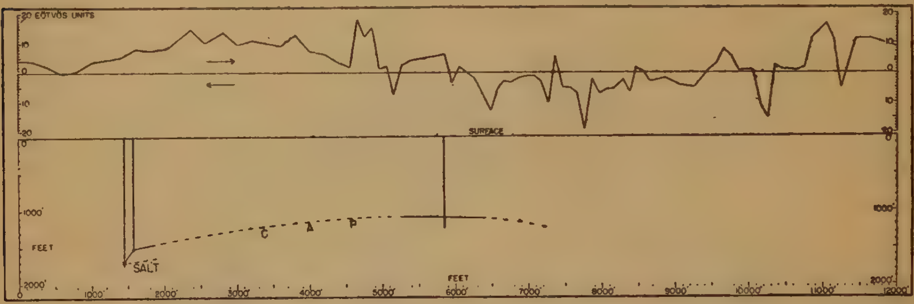

FIG. 9.—DIAMETRAL GRADIENT PROFILE, LAKE WASHINGTON SALT DOME.

Two diametrical profiles were run, one west northwest, east southeast and the other northeast-southwest. The stations were spaced 100 to 300 ft. apart.

The calculations were made in the writer's customary graphical manner. The method of least mean-square deviation of the calculated from the observed gradient profile was used for the determination of the most probable cross section of the cap.

An approximate value for the regional gradient was obtained from pendulum observations of the U. S. Coast and Geodetic Survey, from several local torsion balance surveys 40 to 60 miles to the northeast, north, and west, and from extrapolation of the regional gravity picture from the west and north.

The result of the calculations indicated the presence of a pronounced nose extending several thousand feet northeastward beyond the previously surmised position of the northeastern edge of the dome.

The subsequent exploration for sulphur and the production of sulphur have been

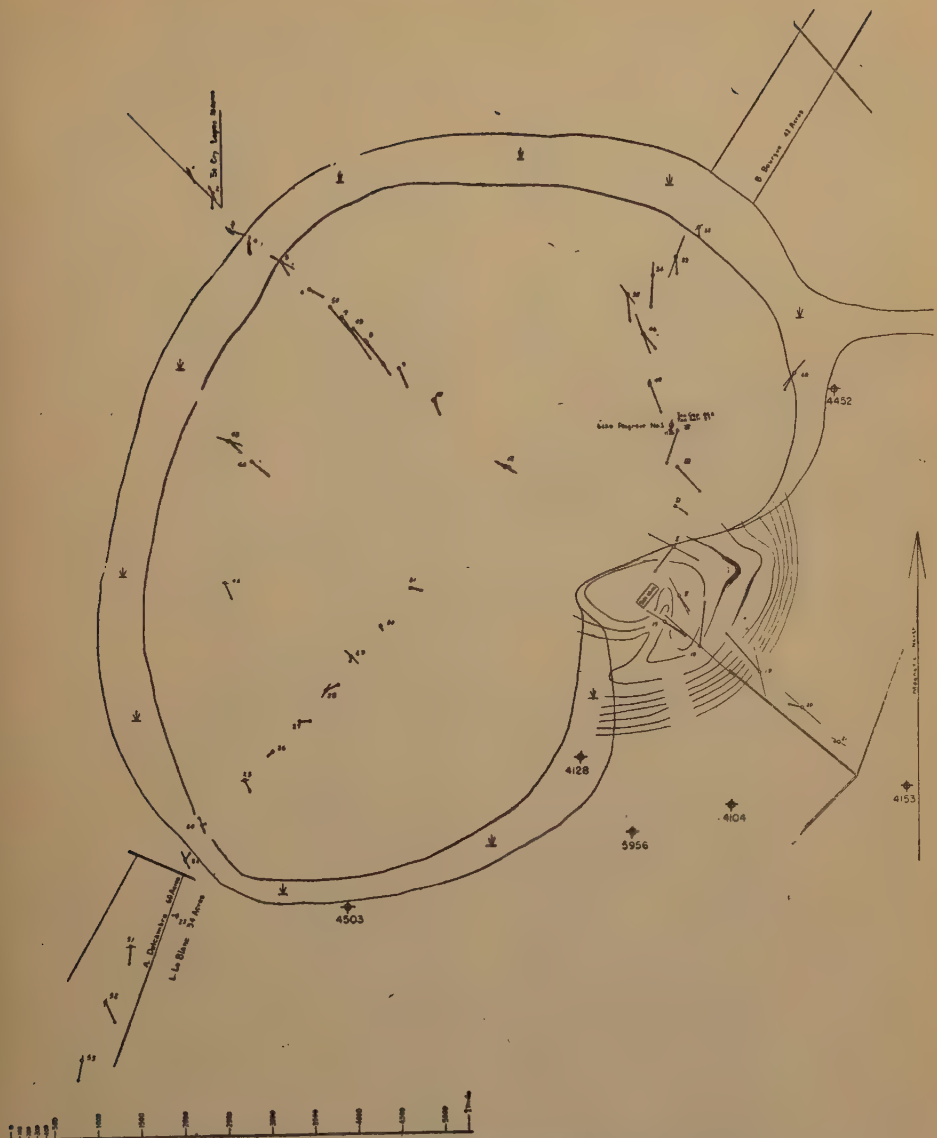

FIG. 10.—GRADIENT-ARROW MAP, TORSION BALANCE SURVEY 1929, JEFFERSON ISLAND SALT DOME. Structure contours on top of salt are below mean sea level. Published by permission of Jefferson Lake Oil Company.

mainly on that nose, and its presence substantially as predicted has been established by the drilling.

Jefferson Island

The situation at Jefferson Island at the time of the quantitative torsion balance survey in 1929 was as follows: A small spine of salt was known to rise within approximately 100 ft. of the surface under the low mound at the east edge of the subcircular Lake Reigneur. The Jefferson Lake Oil Company's No. 1 Lake Reigneur, out in the lake and north of the salt spine,

had encountered cap rock at a depth of 666 ft., the top of the salt at 871 ft., and good showings of sulphur. Another well was being drilled in the near vicinity of Lake Reigneur No. 1. The lake was approximately the size of the salt cores of the other four of the Five Island domes and was surmised to give approximate delineation of the Jefferson Island salt dome.

The problem before the torsion balance was to determine what part or parts of the lake were underlain by considerable thickness of cap rock.

Three profiles were run; a profile of 13 stations along the northwestern radius; a profile of 13 stations along the southwestern radius; and an irregular north-south profile of 16 stations from the north shore of the lake through Lake Reigneur No. 1 and across the salt spine. The two radial profiles were not carried quite to the center of the lake.

The conditions of observation were the worst that have been encountered on any torsion balance survey under the writer's direction. The depth of the water in the lake averages 4 ft. and reaches a maximum of 8 ft., and 43 of the 57 stations were in the lake. The bottom of the lake is very soft silt and gumbo, the thickness of which increases from nothing at the shore to 20 to 35 ft. in the central area.

The torsion balance was set on a wooden tripod of two-by-fours driven into the mud within a triangular iron cofferdam set on bottom. The instrument shelter was set on a square scaffold supported by four two-by-fours driven into the mud. A wooden baffle was dropped from the house into the water to seal the house from the wind and to shelter the iron cofferdam from waves. Log booms were swung on the three sides into the wind and were banked with floating masses of water hyacinth, to break the major force of the waves.

Fully three days of observation was required to get a reasonable set of readings at a few stations, mostly in the central part of the lake. Although the water within the instrument house might seem almost motionless, sufficient vibration was transmitted through the mud to keep the balance system in constant quiver. Usable readings could be taken only during calms or periods of light breezes. During such periods, the quiver of the balance system commonly did not die down completely, but usable readings were obtained by recording the limits of swing for 10 to 20 swings and taking the median position for the desired reading. The method of 180° positions was used; that is, 0°, 180°, 0°, 180°, etc.; and then 90°, 270°, 90°, 270°,—and so on. A lull for 2¼ hr., therefore, would suffice for a set of readings and check for one component of the gradient. An observer was on duty at the instrument night and day, in order to catch such lulls.

A terrane correction was applied for the slope of the hard bottom of the lake.

Calculations for the parameters of the cap rock were made according to the writer's usual graphic method. The trial cross sections for the northwest and southwest radii could not be tied to known depths of the top of the cap and salt at any point, although tentatively the depth to the top of the salt could be assumed with good probability to be approximately the same as in Lake Reigneur No. 1.

The accuracy of the predictions in regard to the cap rock was estimated by the writer to be 60 per cent. The degree of confirmation of the predictions probably would be estimated to be slightly better than 50 per cent. The actual agreement between the predictions and the results of the subsequent drilling is shown graphically in Fig. 11. The edge of the cap was predicted as extending approximately 300 ft. too far out on all three profiles. The error in the prediction of the depth to the cap in general was less than 10 per cent. Qualitatively, the predictions in regard to

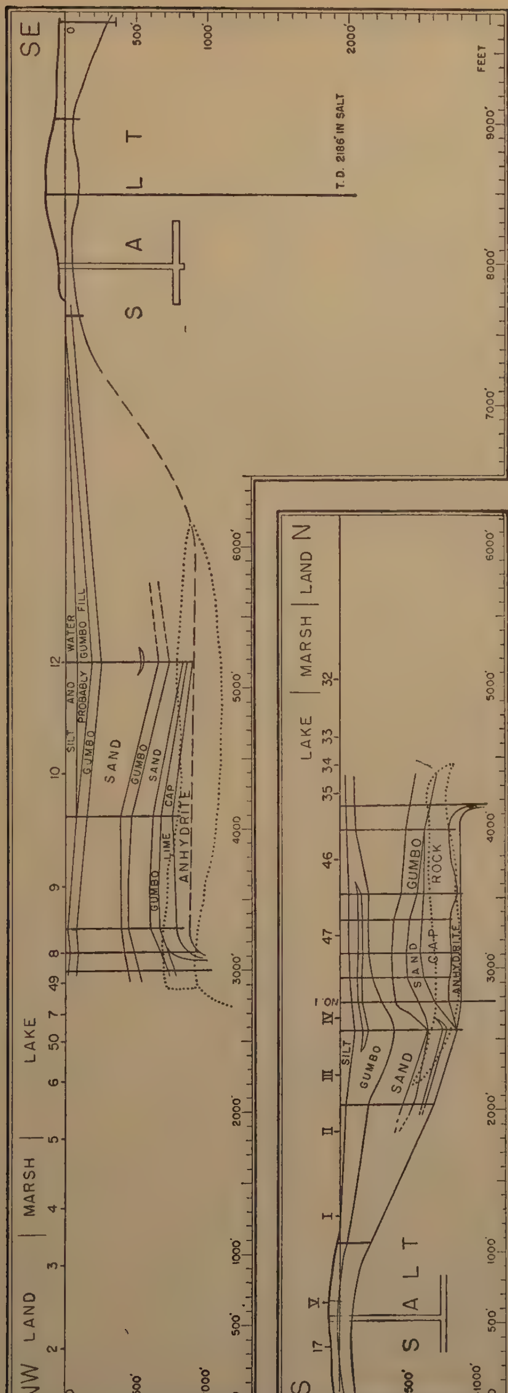

FIG. 11.—NORTHWEST-SOUTHEAST AND NORTH-SOUTH STRUCTURE SECTIONS, JEFFERSON ISLAND SALT DOME.

a. Cap predicted on basis of calculations from gradient data of torsion balance survey.
b. Sections based on the results of subsequent drilling. Data after L. O'Donnell.[12]
Data regarding prediction of cap published by permission of Jefferson Lake Oil Company.

the presence of the cap were correct but quantitatively they were considerably in error. Approximately twice as much cap was predicted as was found and on the southwest profile considerably less cap was predicted than was found. The cap rock was predicted as extending to the foot of the base of the salt spine, whereas it lenses out near the center of the dome. The eastward extension of the cap was based on general principles rather than on the torsion balance data, for there was only one station near the center of the lake and no stations between that point and the salt spine.

The relatively low accuracy of the predictions on this survey compared with those on the other surveys was due to the combined effect of several factors:

1. The observational error at most of the stations presumably was abnormally high.

2. Observation at a sufficient number of stations on each profile was impracticable for several reasons, mostly financial and psychologic. The interval between stations was 300 ft. for a group of four stations near the edge of the cap on the northwest profile, 400 between a few pairs of stations, but mostly 500 ft. or more. Such an interval between stations is much too large unless both the surface and subsurface conditions are exceptionally favorable.

3. The prediction of the edge of the cap too far out seemingly must be related to doming in the beds above the edge of the salt, to overcorrection for the slope of the hard bottom, or to some other factor systematically related to the edge of the dome, for too great extension of the cap outward was predicted on all these profiles. Considerable dip from the last well on the cap to the well off the edge of the cap is shown by O'Donnell's sections. As the doming in those supercap beds extends beyond the edge of the cap, the gradient effect, superimposed upon that of the cap, would tend to indicate too great extension of the cap.

4. The prediction of twice too much cap rock on the northwestern profile in considerable part apparently is the effect of doming of the supercap beds above the cap. They dip gently inward into the central supersalt depression as well as having the normal dip outward.

But in spite of these errors and inaccuracies, the survey substantially accomplished its main purpose in indicating the presence of a large area of cap rock and of showing the area of the dome to be concentric with, but smaller than, Lake Reigneur.

Other Surveys

The other surveys of this type were routine. The edge of the dome in each case was fairly well defined every 70° to 100°. Moderately thick or thick cap rock was known to be present. The task of the torsion balance survey was merely to indicate the position of the edge of the cap in the middle of those sectors.

Résumé of Problem

The determination of the limits, dimensions, and depth of the cap rock of a shallow Gulf Coast salt dome is one of the simplest of the possible quantitative applications of torsion balance surveys, particularly if the depth to the top of the cap and the thickness of the cap are known for at least one point of the survey. The cap is a geometrically simple body, is approximately homogeneous, and has a specific gravity considerably higher than that of the surrounding sediments (2.6 to 2.7 in comparison with 1.9 to 2.1).

The Hoskins Mound survey illustrates the problem in its simplest form. The Bryan Mound, Lake Washington and Jefferson Island surveys represent the problem in more complex forms.

The Bryan Mound survey illustrates the successful handling of masses so small

that the maximum gradient effects were only 1.5 to 2.5 E, gradient values at, or close to, the limit of accuracy of field if the approximate position, size, and relative specific gravity of the causative mass were known, and if, consequently, the

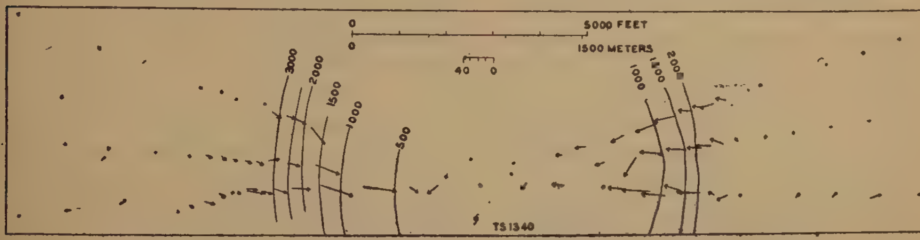

FIG. 12.—GRADIENT-ARROW MAP, BARBERS HILL SALT DOME.

After Barton.[4]
Structure contours indicate depth from surface to top of cap.
Torsion balance survey by Torsion Balance Exploration Company.

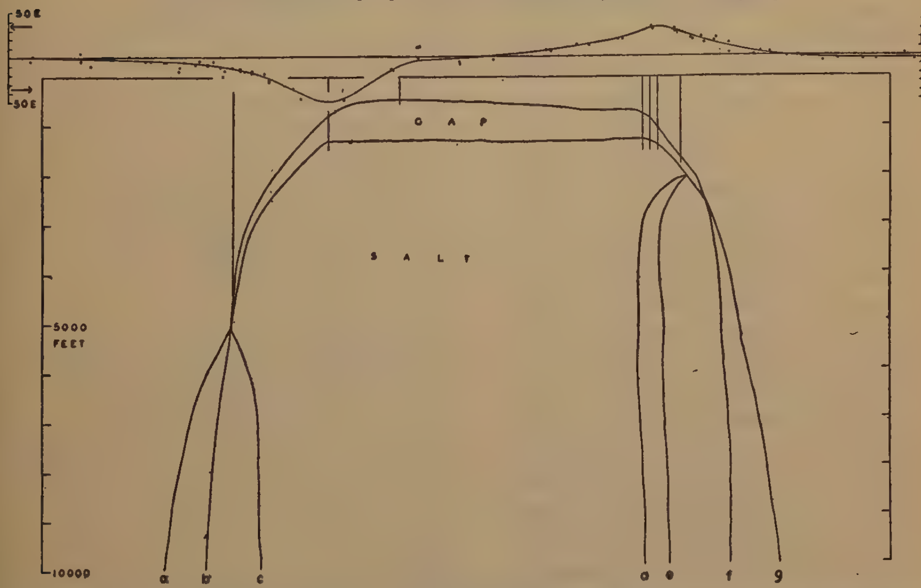

FIG. 13.—SECTION OF TRIAL POSITIONS OF EDGE OF SALT AND GRADIENT PROFILE, BARBER'S HILL SALT DOME.

observation. The success of the Bryan Mound survey suggests the possibility that by doubling the number of stations, and by use of the least mean-square method of comparison of the observed and calculated gradient profiles instead of the visual method of comparison, similar anomalies having a maximum gradient of 1E or perhaps less could be resolved. But success in the use of gradient anomalies of such low amplitude would seem possible only approximate form and position of the anomaly were known.

The Lake Washington surveys illustrate the problem complicated by: (1) unfavorable terrane and presumably, therefore, by abnormally high error of observation, and (2) the necessity of handling a regional gradient as an unknown. The Lake Washington survey illustrates the achievement of semiquantitative, commercially usable, although not completely satisfactory re-

sults in spite of insufficient stations and extremely unfavorable working conditions.

The problem would not be so simple in many other areas; it is simple on the Gulf Coast partly because the geologic situation is simple. The cap-rock mass of high specific gravity is surrounded by beds of rather uniform, relatively low specific gravity. A little "false" cap rock, i.e., Plio-Miocene limestone or secondarily cemented calcareous sands, rests on or against the cap rock on many domes, but its quantity is not sufficient seriously to affect the results of such surveys. Oligocene limestone also is present in moderate thickness on the flanks of several domes and above the cap on at least one dome. Such masses of sedimentary limestone or calcareous sandstone would be mistaken for cap rock in a quantitative torsion balance survey if they lay immediately above the top of the cap or salt or immediately adjacent to the edge of the cap or to the upper flank of the salt, but in other areas limestone makes up a considerable part of the country rock and masses of the limestone are uplifted above the salt-cap core or dragged up along its flanks. Such masses of uplifted limestone would be difficult or impossible to differentiate from cap rock, and if it were upthrust into a massive limestone section the cap rock might have the same specific gravity as the limestone and be indistinguishable from it by any gravitational means. Application of the torsion balance to this type of problem in other areas, therefore, might have less success than evidenced in the Texas-Louisiana Gulf Coast unless the geologic situations were equally simple.

Quantitative Calculations in Regard to the Salt Core

Overhang at Barbers Hill

The presence of overhang such as that at the Barbers Hill salt dome, Chambers County, Texas, apparently can be recognized by careful calculations from the results of a torsion balance survey. In the calculations by the writer in connection with Barbers Hill,[4] the fairly good known data in regard to the form of the top of the cap and the depth of the salt table were taken as known, but the known data in regard to the overhang were assumed not to be known; and the western (left) and eastern (right) flanks therefore were assumed to have one of the forms *a*, *b*, *c*, and *d*, *e*, *f*, *g* in Fig. 13. The gradient effect was then calculated by the writer's graphical method for the cap and for each possible combination of *a*, *b*, *c*, with *d*, *e*, *f*, *g*. The method of least mean and median square deviation of the calculated from the observed gradient profile was used as the criterion for the closest fit between the two curves. Several series of calculations were made, using different assumptions in regard to specific gravities and in regard to regional gradient. The 10 least mean squares and 10 least median squares are given in Table 2.

Table 2.—*Ten Trial Sections and Assumptions Having Least Mean and Median Square Deviations Calculated from Observed Gradient Profiles, Barbers Hill*

Means				Medians			
1.63	*ce*	2.42	*cd*	1.17	*ce*	1.44	*ce*
1.65	*cd*	2.61	*cd*	1.21	*cd*	1.50	*ce*
2.24	*cf*	2.71	*bf*	1.30	*cd*	1.50	*cd*
2.29	*ce*	2.80	*ce*	1.38	*cd*	1.59	*cf*
2.39	*be*	2.80	*ce*	1.44	*ce*	1.69	*cd*

Summary: *ce* 8 places out of the 20; *cd* 8 places; *cf* 2 places; *be* and *bf* each one place.

The combinations of forms of the east and west flanks of the salt core, *cd* and *ce*, stand out as having a much higher degree of probability than any combination containing *a*, *b*, *f* or *g* as one of its members. The deviation of the calculated from the

[4] References are on page 64.

observed gradient profile was so large for *af* that no attempt was made to calculate the mean-square deviation. The forms *cd* and *ce* seem to have about equal probability. The presence of considerable overhang on the east (right) and slight overhang on the west (left) would seem to be indicated by the calculations with a high degree of probability.

The terrane at Barbers Hill is exceptionally good for observations with the torsion balance. The field survey was made by a company that is exceptionally careful in its field work. The error in the observed gradient values of the survey presumably therefore is exceptionally low. The survey was not planned for the problem that was undertaken in this study, and the accuracy of the calculations would have been increased by closer spacing of stations on the profile and by extension of the two ends of the profile farther out from the dome.

These calculations were made after the presence of the overhang at Barbers Hill was well known. The "prediction," therefore, does not have the same validity as though it had come before the discovery of the overhang. But the fact of its existence was not used in the calculations. They, and the least mean-square test for closeness of fit of the observed to the calculated gradient profiles, were routinely mechanical. The test was decisive in indicating the presence of overhang on both sides of the salt core. This study, therefore, would seem to give a legitimate test of the possibility of predicting overhang from the data of torsion balance surveys, at least under favorable conditions.

Prediction of Depth to Top of Salt at Esperson

Prediction of the probable depth to the top of the salt has been made with fair success from calculations from torsion balance data by several geophysicists. Simple inspection of the anomaly commonly is sufficient to allow classification of the salt dome as shallow, moderately deep, or very deep. Calculations are necessary for more precise determination of the depth. Prediction of the probable depth of the salt on the Esperson Dome, Liberty County, Texas, was verified approximately by subsequent drilling. The Esperson salt dome was discovered in the second half of 1928 by a torsion balance survey, which indicated the presence of a deep salt dome. In a study of that survey early in 1930, calculations of the form and depth of the salt were made for the writer according to his standard method. The calculations were not carried to great refinement, and a comparison of the fit of the calculated to the observed gradient profile was made visually. The observed gradient profile, the calculated gradient profile of closest fit, and the corresponding cross section of the salt core, are shown in Fig. 14. The top of the salt was indicated strongly as rising closer than 8000 ft. to the surface but not to within 6000 ft. of the surface, though probably closer to the latter than to the former.

The top of the salt has been shown by drilling to be approximately at a depth of 6000 ft. The Union Exploration Company's 1*A*, which went to a depth of 6014 ft. without encountering salt, is either on or very nearly on the top of the dome. The Kirby Petroleum Company's No. 1 Fee, which is either on the top of the dome or very close to it, drilled through 30 ft. of salt, from 6030 to 6060 feet, but stopped in sand at 6154 ft. The Cranfill and Reynolds Oil Company's No. 1 Moore's Bluff drilled 400 ft. into the salt and stopped in the salt at 7438 ft. The presence of the 30 ft. of salt underlain by sand in Kirby Petroleum Company's No. 1 Fee suggests that the well barely misses the edge of the main salt mass, and that the top of the salt core rises perhaps slightly above 6000 ft. between that well and Union Exploration Company's No. 1*A*. The dotted line in Fig. 14 shows the top of the salt as the writer would surmise it from

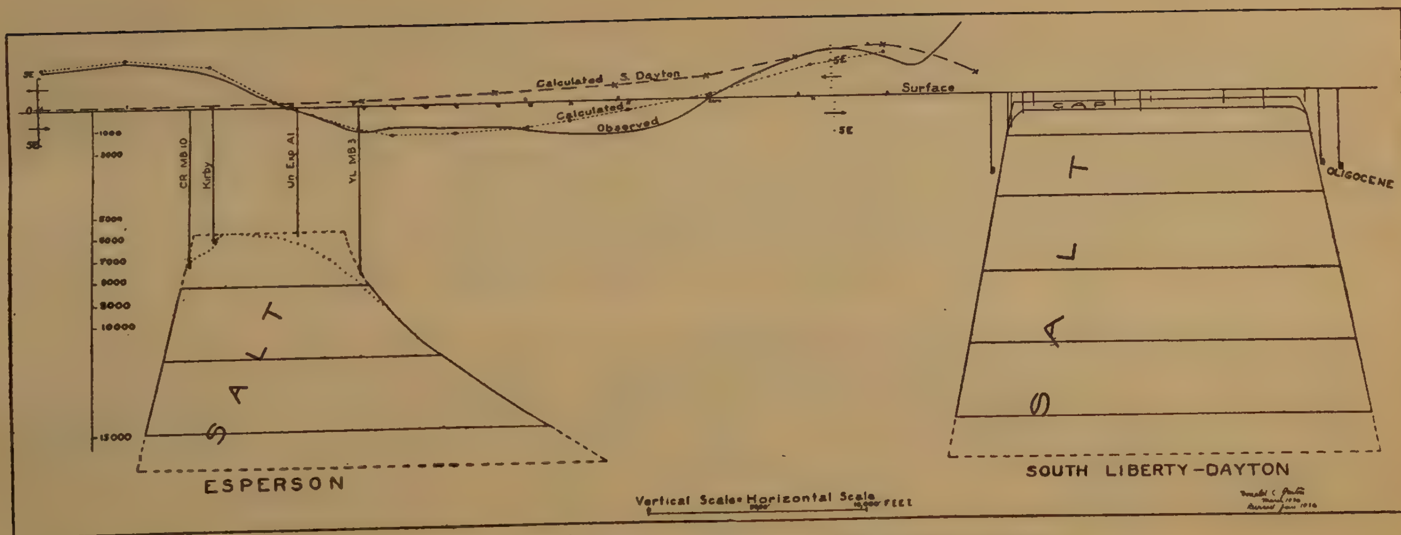

FIG. 14.—SECTION AND GRADIENT PROFILES ACROSS ESPERSON SALT DOME.
Showing observed gradient profile, calculated gradient profile, and top of salt core according to predictions and according to results of subsequent drilling. After Barton.[8]

the well data. The closeness of the dotted to the dashed profile of the top of the salt gives a false impression of very high accuracy in the prediction. The dashed profile represents the shallowest depth that seemed plausible according to the calculations, and the prediction merely asserted that the top of the salt probably was closer to a depth of 6000 ft. than to a depth of 8000 ft. As nothing was known about the depth of the salt at the time of the calculations, the accuracy of the prediction was good.

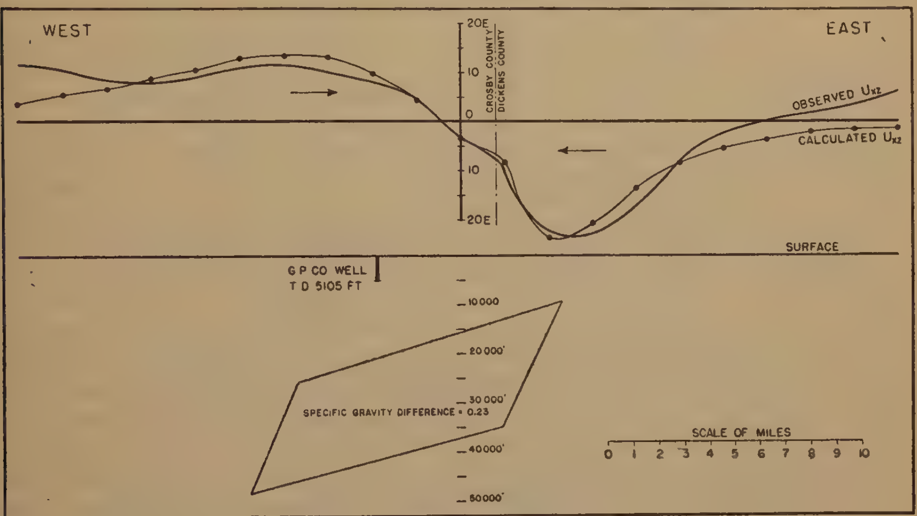

FIG. 15.

Calculation of Position of Crest of a Structure

Mistakes in the interpretation of the position of the crest of a structure in many cases can be avoided by semiquantitative calculations of the form and depth of the mass producing the particular anomaly. Interpretation of the position of the crest of an asymmetric mass is difficult without quantitative or semiquantitative calculations. Asymmetry of a broad, flat, deep mass will not always be recognized by interpretation from simple inspection of the observed gradient, differential curvature and isogam maps. Recognition and interpretation of asymmetry is yet more difficult if a regional gravity anomaly is present. Determination of the position of the crest of a structure with semiquantitative calculations is extremely difficult if the causative mass is deep and lies on or is produced by the deformation of a dipping surface of the basement.

Crosbyton

The Crosbyton anomaly (Fig. 15), Crosby and adjacent Counties, Texas, would seem probably to illustrate the value of semiquantitative calculations. The Crosbyton anomaly is very nearly circular, has an amplitude of approximately 0.045 gal and a diameter of 40 miles. A well was drilled to a depth of 5105 ft. on the crest of the maximum, and as far as can be told the well is structurally normal and the beds encountered are normal, but the control wells are distant.

The asymmetry of the anomaly is not conspicuous in the gradient arrow, differential-curvature map. The asymmetry was not noticed or at least did not impress the writer as important when he made an

interpretation of the anomaly from the torsion balance and magnetic data 10 years ago; hasty calculations on the data then available were included in that interpretation. The asymmetry would seem not to have impressed the geophysicists of the Gulf Refining Co. as important, for the company drilled the well at the crest of the maximum. Careful, tedious calculations made recently by the writer and his former assistant, Mrs. Ethel Ward McLemore, on the basis of the combined torsion balance and pendulum surveys indicate that the upper surface of causative mass has the very asymmetric form shown in Fig. 15. The position of the structural crest in the beds within reach of the drill depends on the character of the tectonic movements affecting that mass as well as on the form of its upper surface. The position of the crest might be over the center of the mass, but the more likely position geologically would be over the eastern peak of the mass. The well, therefore, would seem probably to have been drilled several miles too far west. Structure is not necessarily present, however, in the beds within reach of the drill, for the calculations show that the eastern peak of the causative mass must be at least as deep as 9500 ft. and that if the peak lies at that depth the base of the mass must lie at a depth of 48,500 ft. A magnetic maximum comparable in position, size and amplitude with the gravity maximum indicates that the causative mass has a very high magnetic permeability. The causative mass, therefore, presumably must be a basaltic batholith largely or perhaps wholly within the basement. The tectonic movements associated with the formation of such batholithic masses may or may not continue through or reoccur over long geologic periods, wherefore deformation may or may not be produced in the beds overlying them.*

Theoretical Structure on Sloping Basement

The position of the crest of the structure superimposed on the regionally dipping surface of the basement in Fig. 16 cannot be determined except by calculation of the form of the surface of the basement and the structure on it. If the regional gradient or regional isogams are eliminated, the residual anomaly (a maximum) will be the effect of the mass that is heavily shaded in Fig. 16. The crest of the maximum will be approximately above the center of gravity of that mass and therefore will be shifted considerably to the left from the position of the structural crest of the mass. Satisfactory elimination of regional effects is possible only if the structure is independent of the feature or features that produce the regional variation of gravity; or if the structure rises sharply to a depth that is small compared with the depth of the basement from which it rises. If the structure that produces the structural anomaly is the effect of deformation of a sloping basement surface, the structural anomaly is not independent of the regional anomaly and cannot be satisfactorily separated from it.

Shift of the Crest with Depth

On account of geological shift of the crest with depth, the crest of a structure may not coincide with the position of the crest on the deeper formations that produce the recognizable anomaly. If a body of asymmetric cross section is upthrust vertically into horizontal beds, the position of the crest in those beds will shift away from the steeper side toward the gentler

*Note by C. A. Heiland.—Subsequent to the calculations here referred to, another well (No. 1B Swenson) was drilled by the Gulf Oil Corporation,[6] which found granite at 8104 ft., followed by a second well (No. 1C Swenson) bottomed in granite at 8414 ft. As mentioned above, the best agreement between observed and calculated gradient values was obtained by assuming a three-dimensional parallelopiped dipping at an angle of 15° westward and having a positive density contrast of 0.23. The depth to granite in No. 1B Swenson, however, was only within 40 per cent of the depth to plutonic rock calculated under this assumption.

side with decreasing depth from the surface. If vertical symmetrical uplift takes place in beds having a regional dip, the crest of the structure will shift updip from the point of maximum uplift. If the width of a domal uplift is $2w$, if the maximum height of the uplift at the center is h, and if D is the rate of regional dip, and if we consider the series of cases as D increases from 0 to h/w, the position of the crest of the resultant closed structure will shift updip from the point of maximum uplift; and the closure on the structure will decrease from h to zero. When D becomes h/w, the crest mathematically will reach the updip edge of the zone of uplift, and closure on the structure will vanish. Upthrust that is not vertical will also cause a shift of the crest with depth. The geophysicist may be able to determine the position of the crest of the structure correctly at considerable or great depth, but the position that he determines may not be correct for shallower sands.

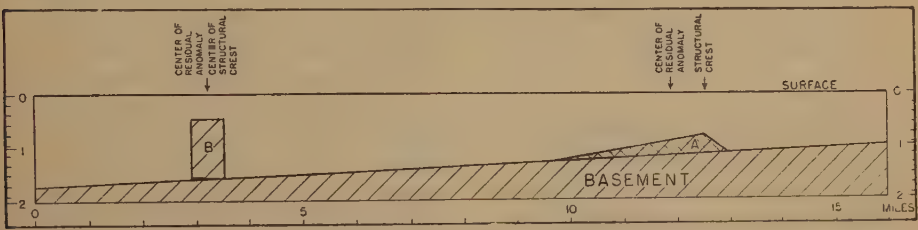

FIG. 16.—STRUCTURES WHOSE RESPECTIVE CRESTS ARE: (*a*) COINCIDENT, AND (*b*) NOT COINCIDENT WITH CREST OF RESPECTIVE GRAVITY ANOMALY.

CONCLUSION

Calculations in regard to the mass causing an observed anomaly are of great value in the interpretation of gravity data, but they are no panacea for the uncertainties of interpretation. The geophysicist should keep the limitations and uncertainties constantly in mind and should see that the users of the results of the calculations are conscious of those limitations and uncertainties. Optimism should be restrained. In some recent attempted sharpshooting for the exact edge of a shallow cap, 1000 ft. thick, of a Gulf Coast salt dome, the predictions in regard to the first two radii were closely confirmed by the drill. One of the two confirmations was spectacularly close, the top of the cap at 500± ft. was within 40 ft. and the bottom at 1000± ft. was within 20 ft. of the respective predicted depths. We were congratulating ourselves on our skill as calculators when the drill showed that our predicted depth on the third radius was 500 ft. too low and on the fourth radius, 200 ft. too low. (Those depths were to points on a flank dipping 50° to 70°.) All factors entering into the calculation are seldom known; and some are only partly known, or known only approximately. The specific gravity relations, for example, are never known exactly. The structural situation—very shallow thick cap, salt core, sediments—apparently presents an ideal clear-cut physical picture but uplift sediments can come in and complicate the structural picture. When the presence of such disturbing beds is known only from whatever surmise of their presence can be gained from the observed variation of gravity, all sorts of combinations of variations in the cap and assumed beds above or against the cap can be obtained that will give rather fair fits of calculated to observed gradient or gravity profiles. The assumed structure in general is much oversimplified,

partly through ignorance of what should be assumed and partly because oversimplification is necessary to reduce the tediousness of the calculation within reason. If the effects of the unknown or neglected factors are small in comparison with those of the main causative mass, calculations in regard to the latter are likely to be successful, perhaps brilliantly successful. But as the effects of the former grow relatively larger, the success of the calculations decreases. A skilled, shrewd geophysicist commonly can recognize whether the accuracy of his calculations is good or poor, but sometimes he cannot do so.

The value of these calculations as a discipline in forcing more accurate interpretation is great, even though quantitatively the accuracy of the results may be poor. Certain limits are given to the range of possible, and of geologically plausible, situations that can produce the observed anomaly. Such limits are brought more vividly to the attention of the geophysicist than would be possible from simple inspection or by analysis without calculation. However, a large range of indefiniteness may be left by the calculations, and widely different situations may produce the observed anomaly under contrasting but equally plausible conditions. A spherical body acts as though its mass were concentrated at the center; an infinite number of spherical bodies can exist, all of whose respective volumes and specific gravities obey the law

$$\text{Vol.} \times \text{Sp. Gr.} = \text{a constant}$$

and all of those spherical bodies will produce identical gravity anomalies. Plausible specific gravities geologically are limited to a very narrow range and the range of spherical bodies that can produce an anomaly is correspondingly limited. But the form of the observed anomaly has a certain haziness. Irregularity is present in every field survey and cannot be smoothed out with certainty. Commonly, also, the parts of the anomaly that lie outside the outer points of numerically one-fourth the maximum gradient are so mixed up with anomalies of adjacent structures as to be unusable. Actually, therefore, a considerable range of chunky but not spherical bodies will also produce that same anomaly within the accuracy of observation. And, as a matter of fact, all concentric chunky bodies of which the product of the respective volumes and specific gravities is constant will produce an identical anomaly, as long as the depth to the body is large compared with all of its dimensions. A series of nonconcentric bodies also may produce an identical anomaly within the accuracy of field observation.[1] Fig. 12 of that reference shows a series of triangles resting on their bases and having their apexes at a common point. All the triangles produce the same anomaly. The results of the calculations never will be free from some degree of indefiniteness but, nevertheless, they definitely throw out certain possibilities and restrict the range of possibilities the geophysicist needs to consider further. According to my experience, the calculations definitely throw out possibilities that previously had looked plausible and bring to mind unthought of new ones that are much more plausible.

Selected References

1. D. C. Barton: Calculations in the Interpretation of Observations by the Eötvös Torsion Balance. Geophysical Prospecting, 1929, 480–504. A. I. M. E., 1929.
2. D. C. Barton: Torsion Balance Survey of Esperson Salt Dome, Liberty County, Texas. *Bull.* Amer. Assn. Petr. Geol. (Sept. 1930) **14**, 1129–1143.
3. D. C. Barton: Belle Isle Torsion Balance Survey, St. Marys Parish, Louisiana. *Bull.* Amer. Assn. Petr. Geol. (Nov. 1931) **15**, 1335–1350.
4. D. C. Barton: Prediction of Overhang at Barbers Hill, Chambers County, Texas —A Study in Quantitative Calculations from Torsion Balance Data. *Bull.* Amer. Assn. Petr. Geol. (Jan. 1935) **19**, 25–36.
5. D. C. Barton: Calculation of the Cap from Torsion Balance Data, Hoskins Mound Salt Dome, Brazoria County, Texas. A.I.M.E. *Tech. Pub.* 719 (July 1936).

6. E. W. McLemore, P. Weaver and D. C. Barton: The Crosbyton Anomaly, Southeastern Crosby County, Texas. *Geophysics* (April 1942) 7(2), 179–191.
7. W. Kennedy: The Bryan Heights Salt Dome, Brazoria County, Texas. Geology of Salt Dome Oilfields, 678–690. Amer. Assn. Petr. Geol., 1926.
8. F. E. Vaughan: The Five Islands, Louisiana. Geology of Salt Dome Oilfields; Cote Blanche, 380–383; Belle Isle, 383–392. Amer. Assn. Petr. Geol., 1926.
9. A. H. Marx: Hoskins Mound Salt Dome, Brazoria County, Texas. *Bull.* Amer. Assn. Petr. Geol. (Feb. 1936) **20**, 155–178; also Gulf Coast Oilfields, 833–856. Amer. Assn. Petr. Geol., 1936.
10. W. L. Goldston, Jr., and G. D. Stevens: Esperson Dome, Liberty County, Texas. *Bull.* Amer. Assn. Petr. Geol. (Dec. 1934) **18**, 1632–1654; also Gulf Coast Oilfields, 857–879.
11. S. A. Judson and R. A. Stamey: Overhanging Salt on Domes of Texas and Louisiana. *Bull.* Amer. Assn. Petr. Geol. (Dec. 1933) **17**, 1492–1520; also Gulf Coast Oilfields, 141–169.
12. L. O'Donnell: Jefferson Island Salt Dome, Iberia Parish, Louisiana, *Bull.* Amer. Assn. Petr. Geol. (Nov. 1935) **19**, 1602–1644; also Gulf Coast Oilfields, 983–1025.
13. H. V. Howe and J. H. McGuirt: Lake Washington Dome in Lower Mississippi River Delta. Louisiana Geol. Survey *Geol. Bull.* No. 8 (1936) 207–242.
14. E. Lancaster-Jones: Computation of Eötvös Gravity Effects. Geophysical Prospecting, 1929, 502–529. A.I.M.E., 1929.

Magnetometer and Direct-current Resistivity Studies in Alaska

By Henry R. Joesting,* Member A.I.M.E.

(New York Meeting, February 1941)

During the past year and a half, the Territorial Department of Mines in Alaska has conducted a modest experimental program for the purpose of determining the extent to which magnetic and resistivity methods can be used in interior Alaska in connection with prospecting, mining and geological studies. Since little information is available concerning previous work,[1,2] and since conditions differ considerably from those in most other regions, it was considered advisable to make a general study of the possibilities and limitations of the two methods, rather than a detailed study of any single problem.

Problems

One of the most serious handicaps to prospecting and geological study in interior Alaska, especially in the mature regions, is a cover of unconsolidated deposits ranging in thickness from a few feet to several hundred feet. These deposits, some of which are permanently frozen, consist of silt with varying proportions of vegetation and windblown material in the valleys and of residual deposits on the hills.[3,4] The problems treated here are caused by the existence of this overburden:

1. Location of buried placers.
2. Determination of depth and areal distribution of permanently frozen and of thawed unconsolidated deposits.
3. Location of water-bearing beds under unconsolidated deposits.

Instruments and Methods

Magnetic and direct-current resistivity methods were used because they are relatively simple, rapid and inexpensive and because generally they are well suited to the study of the problems indicated. The instruments used were a vertical Schmidt-type magnetometer and a direct-current resistivity instrument similar to those used by the Geophysical Branch of the U. S. Geological Survey.[5]

For placer surveys with the magnetometer, a sensitivity of about 25 gammas per scale division was found suitable. For resistivity studies of frozen and thawed overburden and of underground water, the Lee partitioning method[6] was found to be most generally suitable. In the Lee method a central potential electrode is placed midway between the two potential electrodes of the Wenner four-electrode configuration.[7]

Nonpolarizable electrodes were made from unglazed porcelain pots about 10 cm. high and 5 cm. in diameter. In order to retard evaporation of the electrolyte the sides of the pots were glazed, inside and out, with clear Duco lacquer. For resistivity work in cold weather, a nonfreezing electrolyte consisting of equal parts of ethylene glycol and a saturated water solution of copper sulphate proved satisfactory. Stainless steel rods of ¾-in. diameter made excellent current electrodes because their bright finish enabled good ground contacts to be made.

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[1] References are at the end of the paper.

Most of the field work was done during the summer and autumn, although some winter field work was done in order to try out various methods under cold weather conditions; in addition, some swampy areas were more easily worked during the winter. Field methods in general were similar to those used in other regions. Winter work, although slower because of low temperatures and short daylight periods, was found to be entirely practicable.

Mining and prospecting information was obtained when available, for purposes of checking geophysical interpretations. As a rule, interpretations were made entirely independently of these data. Much of the information was given in confidence; hence in some cases it was necessary to omit confirmatory or contradictory data from the graphs showing the results of geophysical measurements.

Location of Buried Placers

The vertical magnetometer appears to be well suited to locating buried placers, since magnetic black sands are commonly associated with placer gold. The magnetometer has been used successfully for placer prospecting in several regions,[1,8–10] but from the information available it was not possible to determine whether it is of widespread value for this purpose, or of value only in a few isolated instances.

In order to determine in a relatively short time the probable applicability of magnetic methods to a large proportion of the placers in interior Alaska, data were obtained concerning:

1. The proportion of placers that contain magnetic minerals in amounts sufficient to cause measurable vertical anomalies.

2. The relations that exist between vertical anomalies, magnetic mineral content and gold content of placers.

3. The effects of anomalies associated with bedrock changes and other causes, on measurement and recognition of placer anomalies.

4. The effect of irregularities in the earth's magnetic field on measurement of placer anomalies.

Magnetic Minerals in Placers

In all, 110 samples of placer concentrates, taken from 54 creeks, were examined in the laboratory, and field tests of placer gravels were made in most of the camps in the interior. Magnetic minerals, the most important of which was magnetite, were found in all the samples. Magnetic picotite or chromite and ilmenite were abundant enough in a few places to have a probable effect on a magnetometer. Other minerals found, of minor importance because of their low susceptibility or scarcity, were iron-rich garnets, amphiboles and pyroxenes, biotite, pyrrhotite, wolframite and platinum. Table 1 shows the approximate magnetite content of placer concentrates grouped according to mining districts.

Table 1.—*Magnetite Content of Placer Concentrates*

District	Number of Creeks	Number of Samples	Approximate Percentage of Magnetite	
			Range	Mean
Chena	6	7	5–15	8
Circle	9	18	1–38	5
Fairbanks	21	49	6–58	14
Koyukuk	3	6	0.5–8	4
Livengood	8	15	15–80	36
Poorman	2	2	20–30	25
Marshall	5	13	6–30	18

Traverses were then run over representative placers in an attempt to determine the relation between magnetite content and vertical anomalies. The results indicate that under favorable conditions measureable anomalies are associated with about three-fourths of the placers in the interior camps considered. Where magnetite content of the concentrates is below about 8 per cent, anomalies may be too small to be measurable. Additional work may alter these estimates somewhat, since the data are incomplete for some districts.

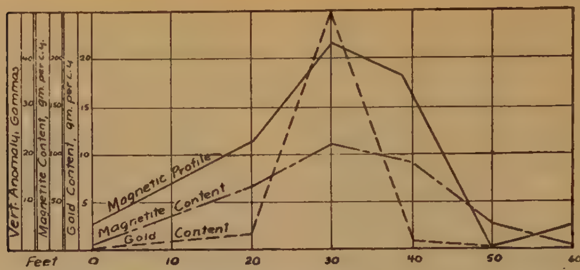

FIG. 1.—RELATION OF MAGNETIC ANOMALY TO MAGNETITE AND GOLD CONTENT IN NARROW BENCH PAY STREAK ON DEADWOOD CREEK, CIRCLE DISTRICT.

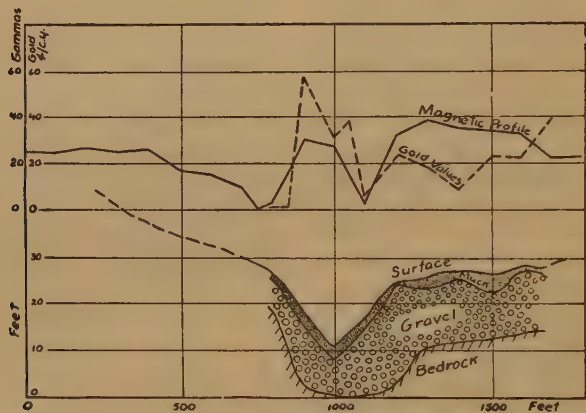

FIG. 2.—PROFILE AT LINE 16, PORTAGE CREEK, CIRCLE DISTRICT.

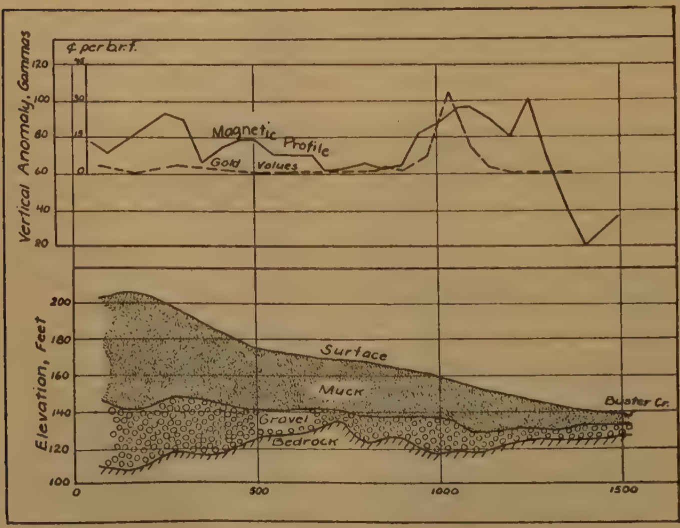

FIG. 3.—PROFILE AT LINE 12, BUSTER CREEK, KAKO DISTRICT.

Relations between Vertical Anomalies, Magnetite Content and Gold Content of Placers

Panning tests show that gold and magnetite occur in roughly proportionate amounts only where there is a well-defined, fairly uniform pay streak. Where gold values are spotted and the gravel is poorly sorted there is often little or no correspondence between the amounts of gold and magnetite. In poorly concentrated placers magnetite is likely to be distributed all along the channel of deposition, whereas most of the gold is deposited a short distance below its source.

Vertical anomalies are usually proportionate to the magnetite content and in most pay-streak placers are also approximately proportionate to the gold content. Fig. 1 shows a profile across a narrow bench pay streak where the vertical anomaly, magnetite content and gold values are in unusually close agreement. The relations are more typically illustrated in Figs. 2 and 3. On Portage Creek (Fig. 2), the magnetite content of the gravel averages 21 grams per cubic yard at the limits of pay and 52 grams in the richer parts. The concentrates from the limits contain about 4 per cent magnetite, compared to 6 per cent in the richer parts. The same general relations hold in other moderately well-defined placers.

In poorly concentrated placers, or in placers where gold is spotted in occurrence, there is little or no relation between anomalies and gold content. However, it is often possible to determine the approximate position of the placer channel, provided that sufficient magnetite is present, although nothing can be determined concerning the distribution of gold within the channel.

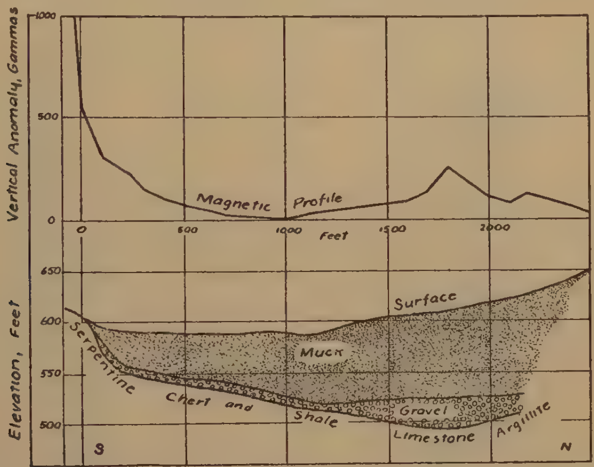

FIG. 4.—PROFILE AT LINE 31, LIVENGOOD CREEK, LIVENGOOD DISTRICT.

Vertical placer anomalies have been found to range from less than 10 to over 300 gammas. Most of them are under 100 gammas and therefore must be classed as small anomalies. They are in general positive; those over deep placers and over uniform pay streaks are usually regular, while those over some shallow placers are very irregular. Figs. 4 and 5 show typical profiles of deep pay streaks and of shallow spotted placers. The irregular anomalies found over some shallow placers may be caused by lodestone or boulders with magnetic fields opposed to the earth's field. Several placers with irregular anomalies were found to contain coarse lodestone.

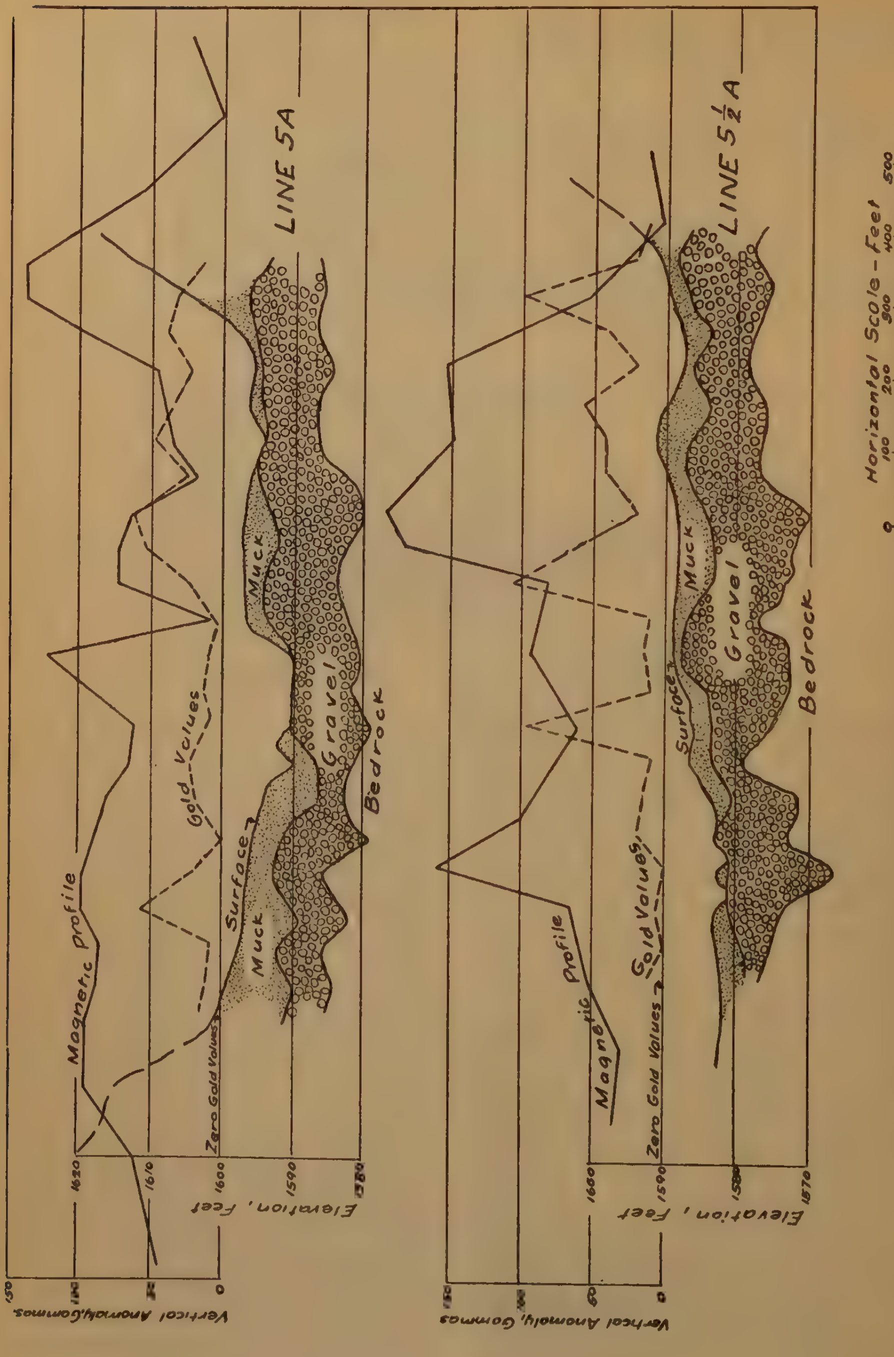

FIG. 5.—PROFILES OF MAMMOTH CREEK, CIRCLE DISTRICT, SHOWING ERRATIC NATURE OF VERTICAL ANOMALIES.

Thick gravel deposits with no marked concentration of magnetite may show anomalies similar in appearance to those caused by deeply buried placers where the depending partly on the size of the intrusive. The pre-Cambrian schist, which is the most widespread bedrock in interior Alaska, usually causes relatively small

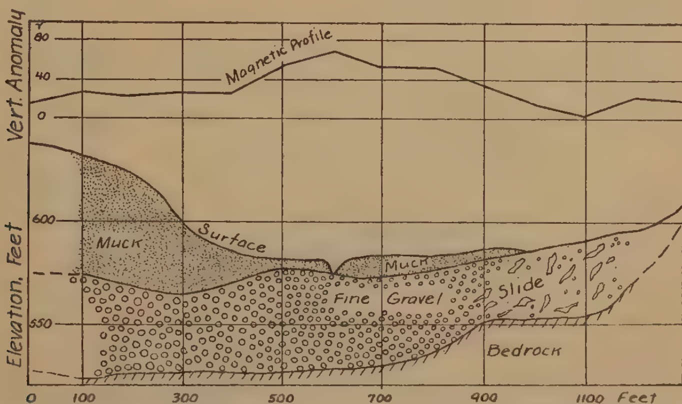

FIG. 6.—PROFILE OF MOOSE CREEK, FAIRBANKS DISTRICT, SHOWING VERTICAL ANOMALY CAUSED BY THICK GRAVEL DEPOSIT. DRILL HOLES 200 FEET APART.

concentration of magnetite is largely on bedrock. This is illustrated by a comparison of Fig. 6, of an anomaly caused by a thick gravel deposit in which there has been little concentration, with Fig. 4, where concentration has caused a definite pay streak.

Bedrock and Other Anomalies Not Associated with Placers

Since placer anomalies are small, magnetic surveys for locating placers must be carried out either where bedrock anomalies are very small or where suitable corrections can be made. A number of traverses were run in areas adjacent to placers and on ridges where no placer anomalies exist, in order to learn something of the size and shape of anomalies over various consolidated formations and to determine whether corrections could be made for their effects.

As might be anticipated, the smallest anomalies were found to be associated with fine-grained sedimentary rocks and the largest with basic igneous rocks. Anomalies associated with acidic intrusives were found to be small to moderate in size, anomalies. Fig. 7 shows a typical traverse profile across chert and limestone bedrock, overlain to the southwest by a poorly concentrated, low-grade placer. The erratic placer anomalies are readily distinguishable from the smaller and more uniform bedrock anomalies. Fig. 8 shows an isodynamic contour map of an area of pre-Cambrian schist. The anomalies, which are small and uniform, are fairly typical of those found over the schist in the Fairbanks and Circle districts.

Corrections for the effects of bedrock anomalies may sometimes be applied in determining placer anomalies. Generally, however, bedrock anomalies large enough to mask placer anomalies are not sufficiently uniform to permit corrections to be made. The practice has been, therefore, to determine the position and magnitude of bedrock anomalies and then search for placer anomalies where bedrock anomalies are unlikely to interfere. For example, during a six weeks placer investigation in the Kako Creek area on the lower Yukon River, about half the time was spent in locating areas of highly magnetic green-

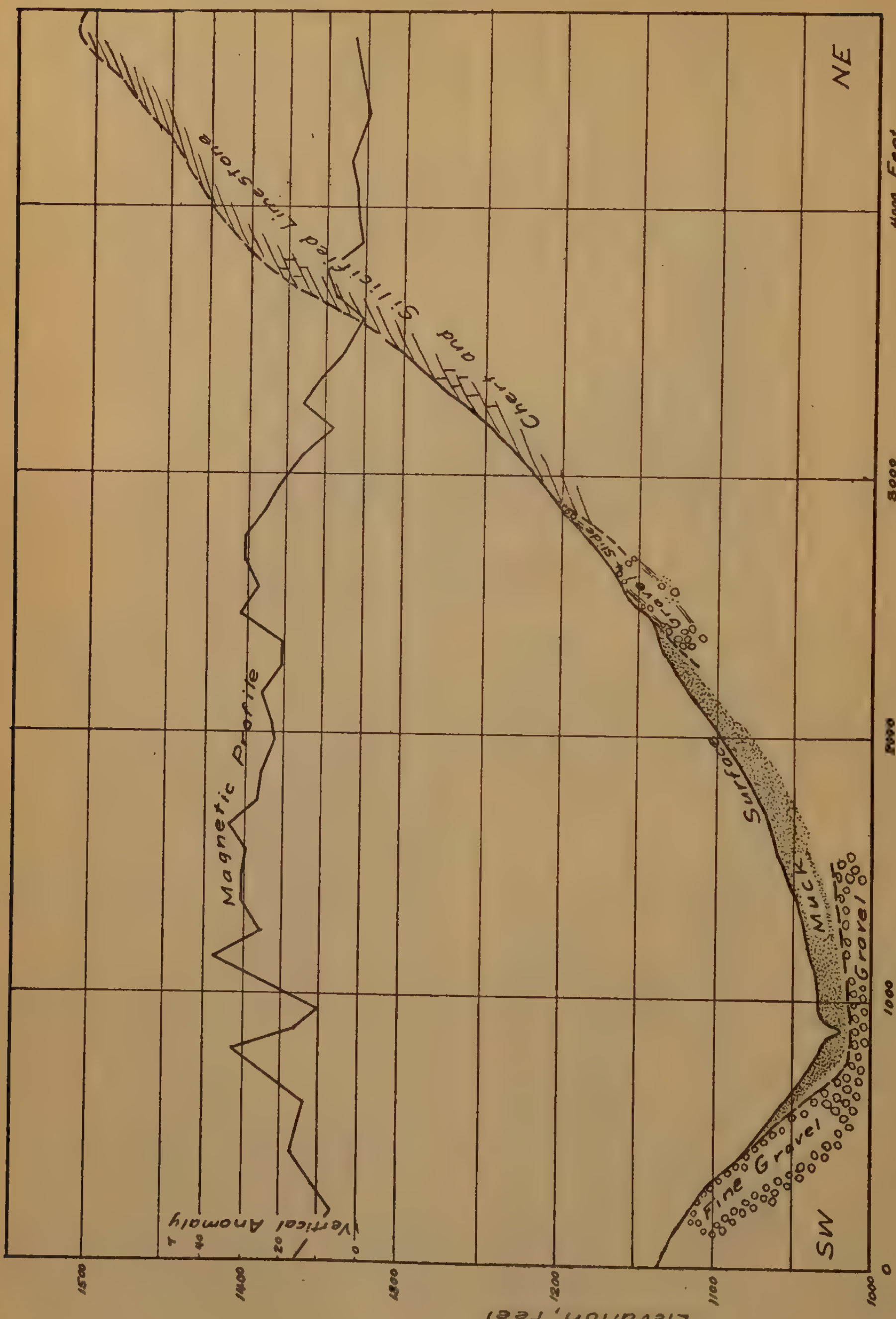

FIG. 7.—PROFILE ACROSS SOUTH FORK OF HESS RIVER, LIVENGOOD DISTRICT.

stone that cross areas of magnetically uniform sediments. The more detailed magnetometric survey for placers was carried out only where sedimentary bedrock was found to occur.

where placers lie across the strike of bedrock. On the other hand, it may be difficult to distinguish between bedrock and placer anomalies where the placer channel parallels the strike of bedrock.

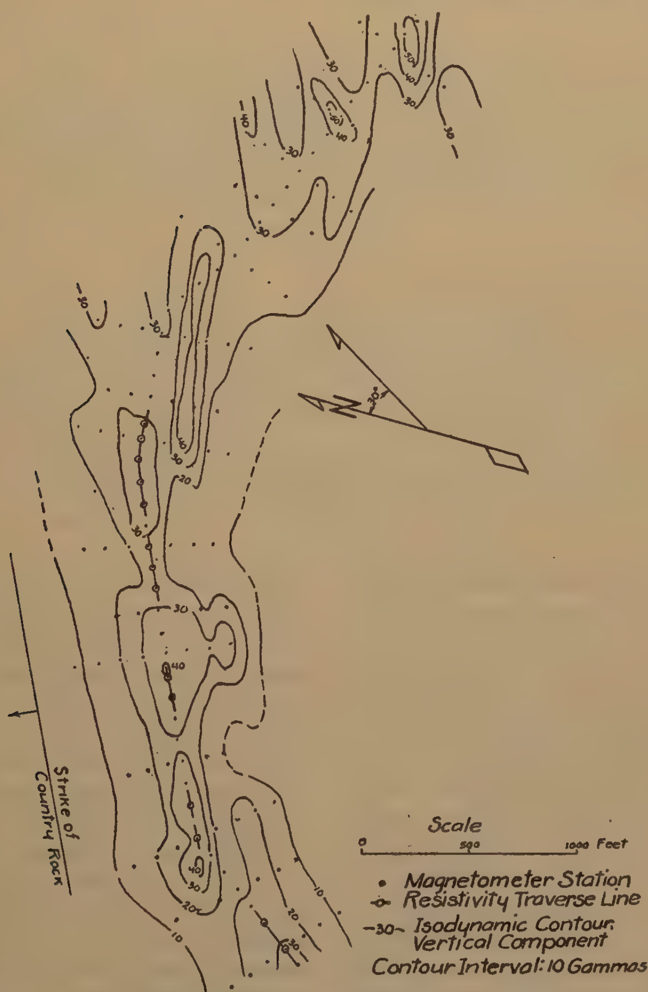

FIG. 8.—MAGNETOMETRIC MAP OF RIDGE ON SOUTH SIDE OF GOLDSTREAM CREEK, FAIRBANKS DISTRICT.
Sections 19 and 20, T. 1N., R. 1W.

Sedimentary rocks and metamorphosed sediments have been found to be magnetically more uniform along their strike than across their strike, consequently bedrock anomalies are unlikely to interfere

Silt overburden apparently has a low and relatively uniform susceptibility, nevertheless small anomalies result from abrupt changes in slope, such as occur at silt benches or where deep, narrow gullies

are cut into the overburden. They are termed here topographic anomalies, and possibly may be caused by magnetic screening, or distortion of the field to conform to the surface. Because of topographic anomalies, the vertical intensity decreases slightly at the bottom of benches and gullies, and increases along the sides. The size and shape of these anomalies apparently depends on the surface configuration as well as on the magnetic susceptibility of the overburden. The largest topographic anomaly measured is 45 gammas; usually they do not exceed 20 gammas. Approximate corrections are necessary in determining placer anomalies when the latter are likely to be small, or when topographic and placer anomalies are likely to coincide in position. Since for a given type of surface irregularity topographic anomalies are likely to be uniform within limited areas, these corrections can be made on the basis of field measurements.

Vertical magnetic profiles across narrow, steep-sided valleys also show some anomalies similar in form and origin to those caused by narrow gullies in overburden, and for this reason the vertical intensity along the ridges and valley sides may be higher than in the valley floor. Corrections usually are unnecessary for this type of topographic anomaly, since it seldom coincides in position with that associated with placers.

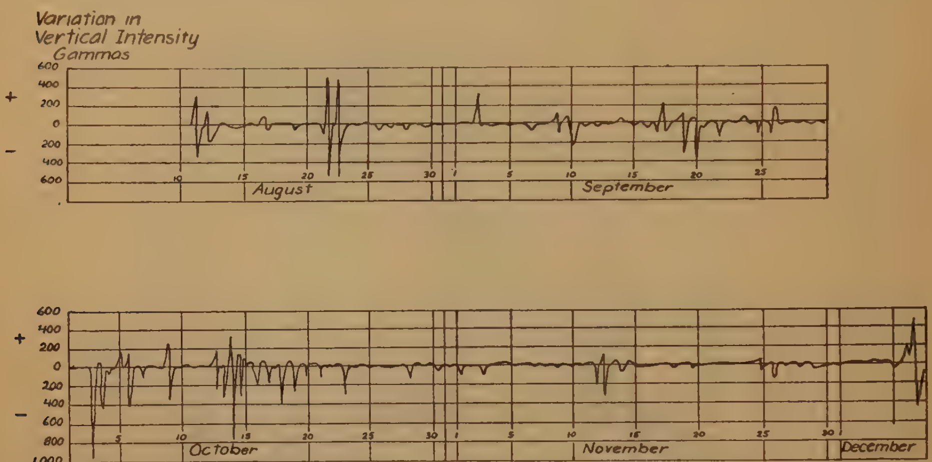

FIG. 9.—MAJOR VARIATIONS IN VERTICAL COMPONENT OF MAGNETIC FIELD, AUG. 11 TO DEC. 6, 1939.

Irregular Variations in the Earth's Field

Magnetic storms are comparatively frequent and intense in high latitudes. In interior Alaska they may cause changes of 500 gammas or more within a few minutes in the vertical component. Figs. 9 and 10, condensed from magnetograms supplied by the Sitka Magnetic Observatory and from field data, show the major fluctuations in the earth's field intensity during parts of the 1939 and 1940 field seasons.

Since only one vertical magnetometer was available, it was not possible to measure placer anomalies during even slight disturbances. An effort was made to correlate changes in vertical intensity at Sitka with those near Fairbanks, but the agreement was not close enough to enable corrections to be applied to field measurements on the basis of the Sitka magnetograms. Finally, through the cooperation of the Sitka Observatory, forecasts of magnetic conditions were obtained, which

enabled calm periods to be utilized exclusively for measuring small anomalies. In addition, copies of daily magnetograms were supplied in order that an approximate check could be maintained on the diurnal variation curves obtained in the field from hourly readings at base stations.

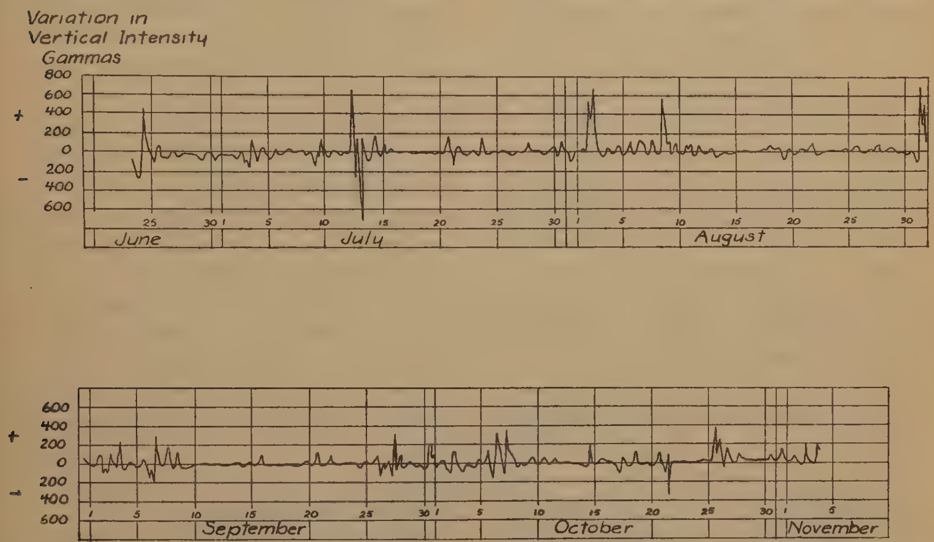

FIG. 10.—MAJOR VARIATIONS IN VERTICAL COMPONENT OF MAGNETIC FIELD, JUNE 23 TO NOV. 4, 1940.

The principal disadvantage of measuring small anomalies with a single instrument is that much time is lost because of the necessity for frequent base-station readings. Although the results are somewhat less accurate than when a separate base instrument is used, the maximum error under most conditions was about 10 gammas, and the mean error was generally not over 6 gammas. This accuracy is sufficient for measuring most placer anomalies.

Table 2, taken from Sitka magnetograms, shows the relative number of quiet and disturbed days during parts of the field seasons of 1939 and 1940. Days or fractions of days during which changes in vertical intensity were small and uniform are considered quiet; disturbed days include those during which small but irregular fluctuations, as well as magnetic storms, prevented the measurement of vertical anomalies smaller than about 20 gammas. Although it is possible to plan field work so that little time is lost because of magnetic disturbances, nevertheless they are a serious handicap to measuring small anomalies in Alaska with field methods now in use.

TABLE 2.—*Comparison of Quiet and Disturbed Days*

Month	Number of Quiet Days	Number of Disturbed Days	Total Days	Percentage of Disturbed Days
AUG. 11 TO DEC. 6, 1939				
August	14	7	21	33
September	23	7	30	23
October	22	9	31	29
November	27	3	30	10
December	5	1	6	17
Total	91	27	118	23
JUNE 24 TO OCT. 31, 1940				
June	4	3	7	43
July	15	16	31	52
August	22	9	31	29
September	21	9	30	30
October	23	8	31	26
Total	85	45	130	35

Thawed and Permanently Frozen Overburden

In order to determine the resistivities of various unconsolidated and consolidated rocks, about 400 field measurements were made in the Fairbanks, Livengood and Circle districts, where subsurface conditions were known through drilling or mining operations. Most of the resistivity measurements were made during the summer months when the surface was more or less thawed, but some in the Fairbanks district were made during midwinter at temperatures as low as minus 30°C.

Resistivities were calculated by Roman's method[11,12] when the depth profiles approximated theoretical two-layer curves. In some cases resistivities were sufficiently uniform to be taken directly from the depth profiles; in others, conditions were too complicated to permit determination of the resistivity of any single layer. The results are summarized in Table 3.

Variations in the moisture content of the near-surface material were responsible for the wide resistivity range of thawed unconsolidated deposits. At depths greater than 5 ft. the moisture content was more uniform and there was less variation in resistivity.

Thawed, moist silt appears to have higher resistivity than comparable material in lower latitudes. This may be due to the comparatively small amount of clay in much of the overburden and to lower ground temperatures. Rock weathering in interior Alaska is accomplished principally by freezing and thawing; in addition this process plays an important part in the transportation of rock debris. Chemical and biochemical processes are unimportant because of low temperature, scant rainfall and restricted underground circulation. The result is that much of the overburden consists of unaltered, comminuted rock fragments with relatively small amounts of clay.

Thawed, moist gravel has a higher resistivity than thawed silt, and water-bearing gravel has a higher resistivity than moist gravel. Lee[3] and others attribute the higher resistivity of water-bearing beds to the smaller content of dissolved salts in water with unrestricted circulation. In addition, many of the moist gravel deposits

TABLE 3.—*Resistivities of Thawed and Frozen Overburden and Bedrock*

Material	Resistivity Range, Ohm-cm.	Approximate Mean Resistivity, Ohm-cm.	Locality*
Thawed, moist silt and vegetation muck (in valleys)	3,600– 35,000	1.1×10^4	*a,b,c,*
Thawed silt and residual deposits, dry on surface (on slopes)	20,000– 190,000	4.0×10^4	*a,b,c*
Frozen silt and vegetation muck	200,000– 800,000	36.4×10^4	*a,b,c*
Thawed moist sand, fine gravel and clay	22,000– 65,000	4.2×10^4	*a,b,c*
Thawed moist gravel	41,000– 71,000	5.5×10^4	*a,b,c*
Water-bearing gravel	100,000– 185,000	13.5×10^4	*a,b,c*
Frozen sand and fine gravel	630,000–2,400,000	120×10^4	*a,b,c*
Frozen gravel	780,000–4,100,000	220×10^4	*a,b,c*
Frozen surface silt at −10°C	2,000,000–3,000,000	220×10^4	*a*
Frozen surface gravel at −15°C	2,500,000–4,000,000	350×10^4	*a*
Thawed soft mica schist, chlorite schist and graphitic schist	20,000– 80,000	3.9×10^4	*a,c*
Thawed hard quartzitic schist	200,000– 300,000	26×10^4	*a,c*
Thawed conglomerate	22,000– 70,000	6.0×10^4	*c*
Frozen conglomerate	1,200,000–1,600,000	140×10^4	*c*
Thawed chert	140,000– 200,000	17×10^4	*b*
Thawed limestone	50,000– 84,000	6.5×10^4	*b*
Thawed argillite	26,000– 70,000	5.7×10^4	*b*
Thawed granite	95,000– 185,000	15×10^4	*c*
Thawed serpentine	114,000– 140,000	12×10^4	*b*
Partly frozen limestone and serpentine	270,000–1,500,000	57×10^4	*b*

* *a*, Fairbanks district; *b*, Livengood district; *c*, Circle district.

investigated contain more fine material than the water-bearing gravel, which apparently lowers their resistivities.

Although the resistivities of frozen silt and gravel are from 20 to 50 times those of their thawed counterparts, much higher values might be anticipated in view of the resistivity of pure ice (4.4×10^8 ohm-cm. at $-4°$C.*).† However, since the ice in permanently frozen ground is not pure, it is probable that electrolysis, or some analogous process, plays a part in the conduction of current, with the result that resistivity is lower than if conduction were entirely ohmic. As it is difficult to conceive of electrolytic conduction through a solid, it may be necessary to postulate the existence, in the frozen silt, of minute layers or cells of liquid electrolyte in equilibrium with the ice. Evidence that electrolytic processes are active at temperatures far below freezing was obtained when iron rods were driven a few inches into frozen silt. Potentials as high as 0.3 volt were set up between pairs of rods in midwinter when the air temperature was minus 30°C. and the ground temperature was about minus 20°C. Potentials dropped to a few millivolts when nonpolarizable electrodes were substituted for the iron rods.

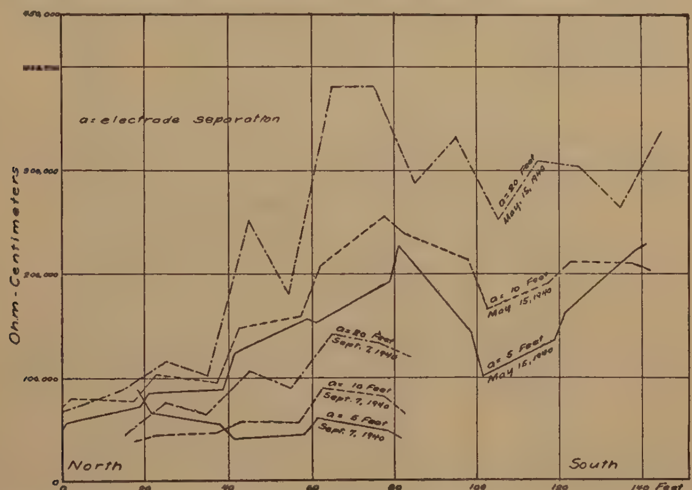

FIG. 11.—TRAVERSE PROFILES SHOWING RESISTIVITY INCREASE FROM THAWED TO PERMANENTLY FROZEN GROUND.

The wide range in resistivity of frozen silt and muck may be partly explained by temperature differences in different deposits. It is known that temperature differences exist, but no measurements have been made in the regions considered here.[13] Another possible reason for some of the lower values is that occasional thawed parts may occur in some of the ground reported to be completely frozen on the basis of drill logs. It is often difficult to detect thawed patches, or partly thawed ground, by churn drilling.

Frozen and thawed ground can readily be differentiated by resistivity measurements. Traverse profiles are suitable for determining the areal distribution of frozen ground, while depth profiles enable the approximate depth to be determined. Fig. 11 shows typical resistivity traverse profiles, extending from thawed silt and fine gravel on the north to similar frozen deposits on the south. The contact is at

* International Critical Tables, 6, 152.

† No information was available to the author when this paper was written concerning the resistivities of dilute electrolytes in the frozen state.

35 ft. on the profile and dips north. Resistivities were determined every 20 ft. at electrode separations of 5, 10 and 20 ft. The May 16 profiles were run when the thawed surface layer was only a few inches thick. By Sept. 7, when the second traverse was run, the surface thaw had extended to depths of 1 to 3 ft., and for that reason the apparent resistivities of the frozen ground are much lower.

Approximate depths of permanent frost are usually obtainable from resistivity-depth profiles because there is a sharp decrease in resistivity when the electrode spacing approaches the depth at which thawed ground is encountered (Figs. 12, 13 and 14). In Fig. 12 the lower summer resistivities are caused by a 1 to 3-ft. surface layer of thawed silt. Winter resistivities are relatively low at 10 ft. because in December, when the measurements were made, the bottom of seasonal frost had not reached the top of permanent frost. Actual depths to thawed ground and

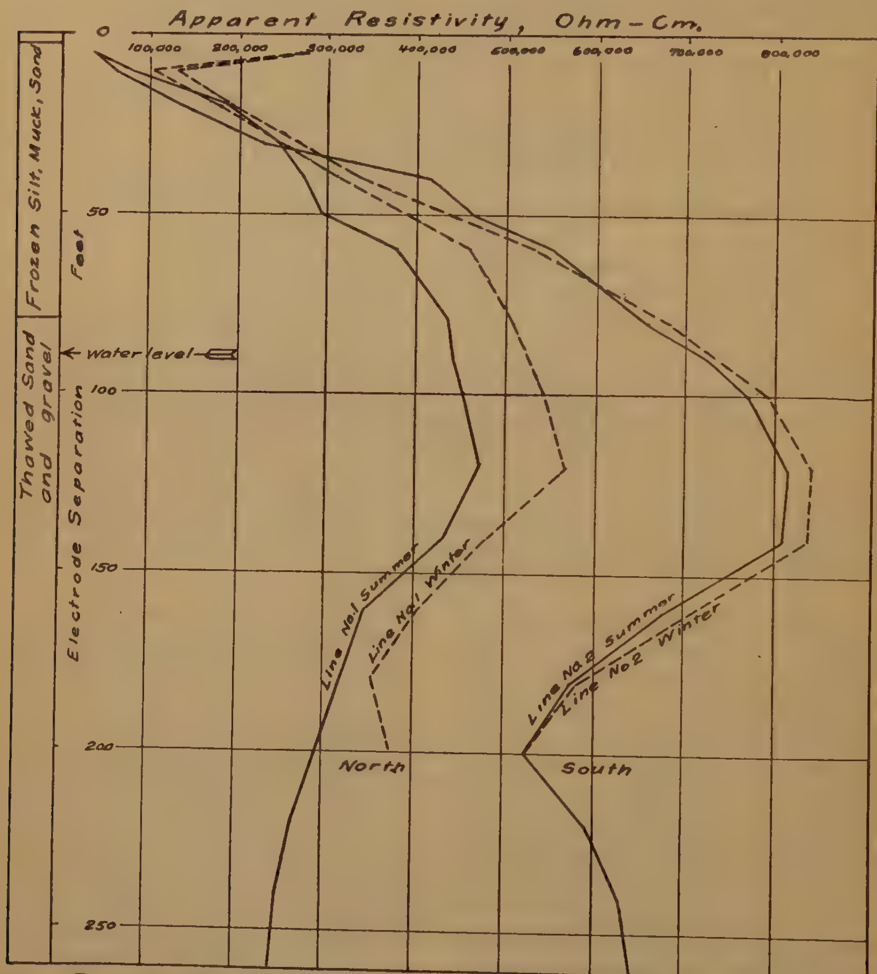

FIG. 12.—DEPTH PROFILES IN PERMANENTLY FROZEN OVERBURDEN, TANANA VALLEY, NEAR COLLEGE, ALASKA.

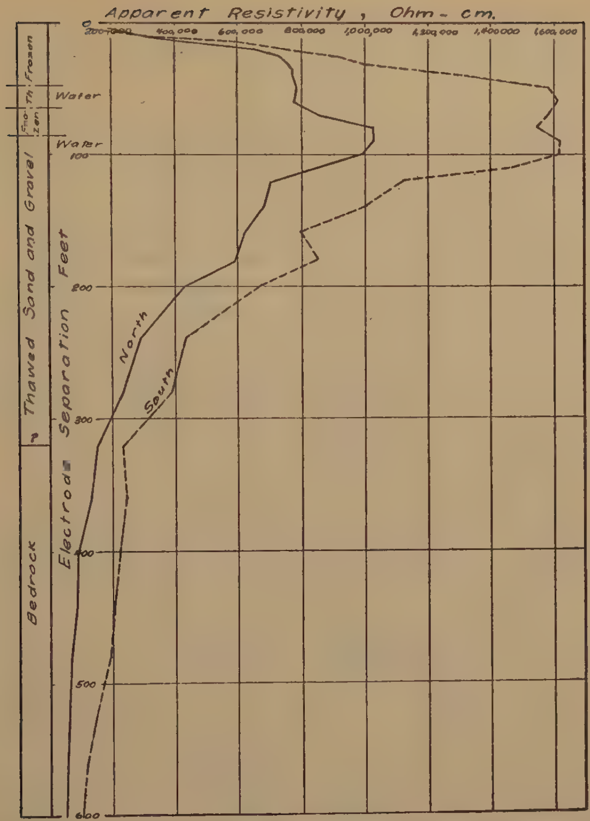

FIG. 13.—DEPTH PROFILES IN PARTLY FROZEN OVERBURDEN, TANANA VALLEY, EAST OF FAIRBANKS.

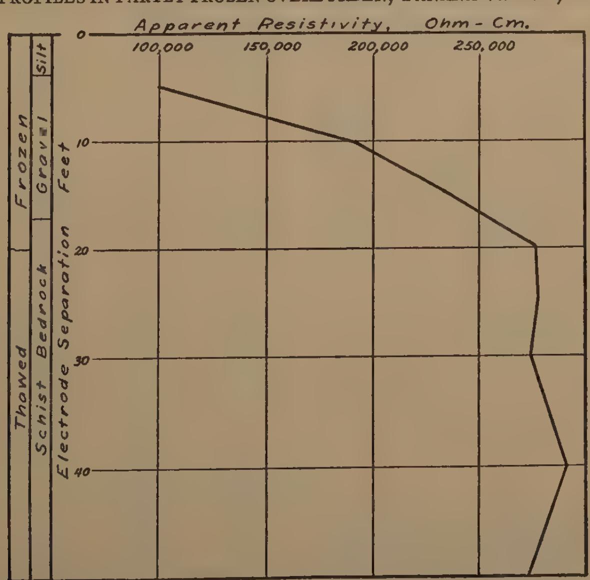

FIG. 14.—DEPTH PROFILE IN PERMANENTLY FROZEN GROUND, MAMMOTH CREEK, CIRCLE DISTRICT.

to water were obtained from the log of a well driven 150 ft. west of line No. 1. The actual depth to the schist bedrock is not known, but it is probably between 125 and 150 ft. and increases to the south.

Fig. 13 is shown principally because the apparent resistivity is the highest obtained in this investigation. The resistivity of the upper layer is calculated to be approximately 7,000,000 ohm-cm., but because of the steep slope of the resistivity-depth curve, this value may be somewhat in error. The log of a well located 500 ft. N. 30°E. from the central electrode shows frozen silt, sand and gravel to a depth of 80 ft., except for a layer of water-bearing sand from 44 to 55 ft. Water-bearing gravel was struck at 80 ft., followed by thawed fine gravel and sand to a depth of 277 ft., where drilling was discontinued. Depth to schist bedrock is estimated to be over 300 ft. In view of the lenticular nature of river deposits, the north resistivity-depth curve, which is closer to the well, is in good agreement with known conditions.

Fig. 14 shows the mean of four closely agreeing sets of resistivity measurements made in four directions from the same point. Here the break in the curve occurs not at the stratigraphic break, but at the lower boundary of frost. As frost seldom extends far into bedrock covered by thick overburden, in some places approximate depths to bedrock can be determined indirectly by determining the depth of frost.

Approximate determinations of thickness of silt and gravel were found to be possible only where conditions were fairly simple. Determinations of depths were sometimes impossible because the resistivity of the overburden was not measurably different from that of the overlying bedrock; in other places the lack of horizontal uniformity confused the interpretation of depth profiles.

Fig. 15 illustrates the case where there is no apparent break between overburden and bedrock. The meaning of the break at an electrode separation of 50 ft. is not known, as it is doubtful whether frost extends 30 ft. into bedrock. In Fig. 16, although there is no abrupt change in resistivity when the electrode separation equals depth to bedrock, a satisfactory determination of the thickness of the upper layer is obtained by the use of Roman's superposition method.[10]

Irregularities in resistivity are caused by the lenticular nature of the unconsolidated deposits and by the frequent occurrence of irregular masses of frozen ground. Fig. 17 illustrates the effect of lack of horizontal uniformity that occurs in many of the deeper placers. Here the schist bedrock surface is irregular and so deeply decomposed that depths are known only approximately. The silt overburden is mostly frozen, while the underlying gravel is frozen and thawed in about equal parts. Drill logs show, to the north of the central electrode, 75 ft. of frozen silt overlying 100 to 105 ft. of frozen gravel, and to the south 70 ft. of frozen silt overlying 70 ft. of thawed gravel. To the east and west the mean depths are 50 ft. of frozen silt and 115 ft. of gravel. The resistivity-depth profiles indicate that frozen ground, with occasional thawed lenses, occurs from depths of about 10 ft. to bedrock. The meaning of the resistivity maxima at 220, 260 and 270 ft. is not known. Although some of the changes in slope can be correlated with drill data, the determination of depths without the aid of near-by drill holes would be extremely hazardous.

In Fig. 18 are shown two of a series of depth profiles obtained in the Tanana Valley near Fairbanks. They indicate some possible uses of resistivity measurements in studying thick fluvatile deposits that are partly thawed and partly frozen (see also Figs. 12 and 13). Although there is considerable small-scale horizontal variation, when large masses of these deposits are measured there is sufficient lateral

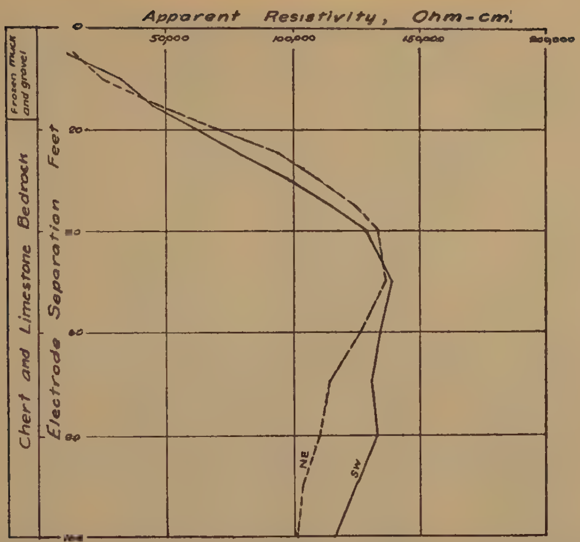

FIG. 15.—DEPTH PROFILES IN PERMANENTLY FROZEN GROUND ON LIVENGOOD CREEK, LIVENGOOD DISTRICT.

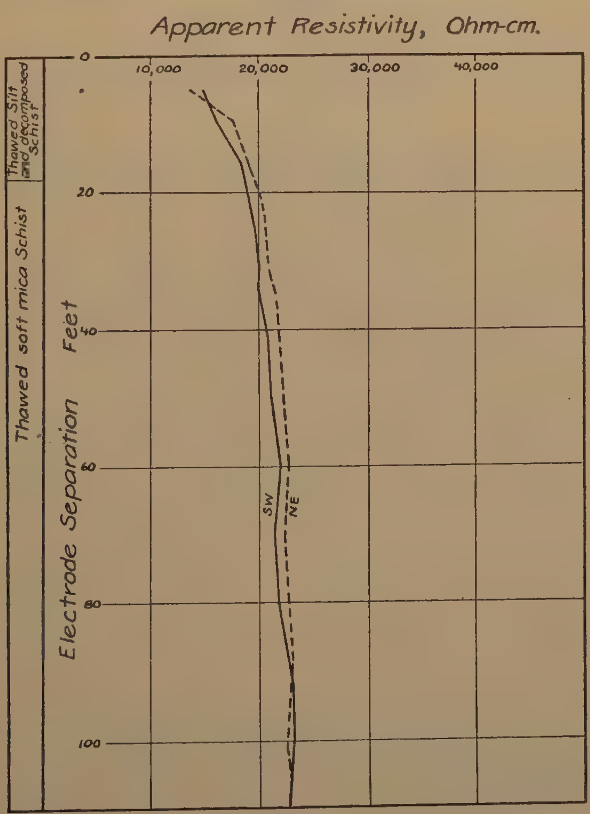

FIG. 16.—DEPTH PROFILES IN THAWED OVERBURDEN AND SCHIST BEDROCK, NEAR GOLDSTREAM CREEK, FAIRBANKS DISTRICT.

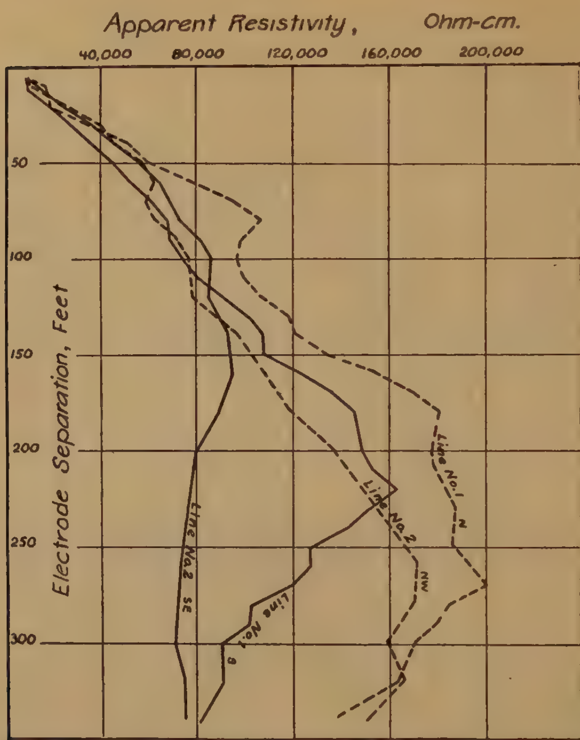

FIG. 17.—DEPTH PROFILES IN PARTLY FROZEN OVERBURDEN, ESTER CREEK, FAIRBANKS DISTRICT.

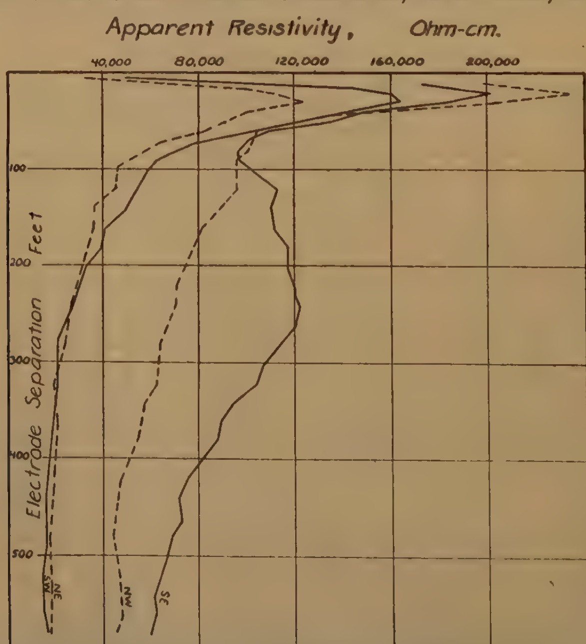

FIG. 18.—DEPTH PROFILES IN PARTLY FROZEN OVERBURDEN, TANANA VALLEY, NEAR FAIRBANKS.

uniformity in resistivity to enable approximate depth determinations to be made.

The greatest known depth reached by drilling in the river deposits near Fairbanks was 364 ft. Since bedrock apparently was not struck, it may be at least 400 ft. below the surface in some places. According to available well logs, the ground is alternatingly thawed and frozen to a depth of about 180 ft. The proportion of thawed ground increases with depth and probably below 180 ft. it is entirely thawed. Shallow water-bearing gravels are encountered in areas where the surface is thawed and in addition a lower water level occurs at depths of about 80 to 100 feet.

Resistivity-depth profiles obtained near Fairbanks are substantially in agreement with well logs concerning the depth and distribution of frozen ground. Indications of bedrock, which have not been checked by drilling, have been obtained at depths of from about 300 to 450 feet.

Underground Water

Where silt and gravel deposits are thick, the underlying gravel is more likely to be thawed than the silt. Thawed gravel layers are also common in thick river deposits, like those near Fairbanks. As a rule, thawed gravel deposits are water-bearing; therefore, resistivity traverse profiles afford a simple and rapid means of locating thawed areas, and incidentally water, in otherwise frozen sand and gravel deposits (Fig. 11). Depth profiles can be used also for locating water under frozen deposits by determining the depth at which thawed ground is encountered (Figs. 12, 13 and 18).

Where the ground is thawed, the problem of locating underground water is more difficult because of the frequent lack of uniformity in the overlying beds and because the differences in resistivity are not as great as between thawed and frozen

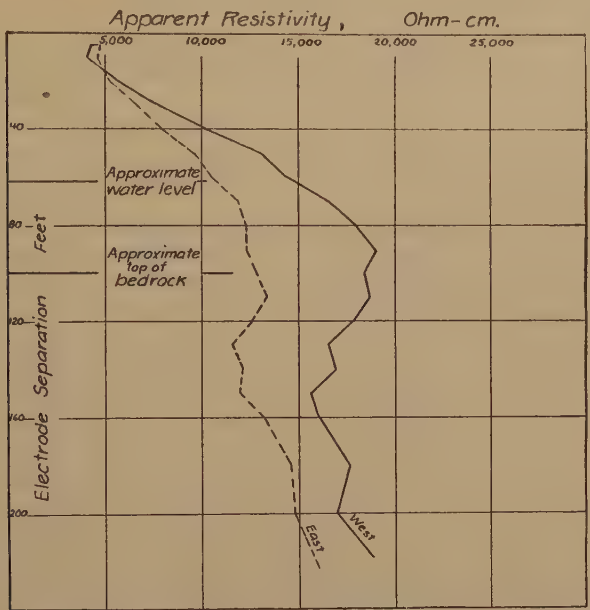

FIG. 19.—DEPTH PROFILES IN THAWED SILT AND WATER-BEARING GRAVEL, NEAR ESTER CREEK, FAIRBANKS DISTRICT.

beds. Under favorable conditions, however, water-bearing gravel can be found at considerable depths. Fig. 19 shows one surface. The low temperature of the water, 3°C, may partly account for the high resistivity of the south line.

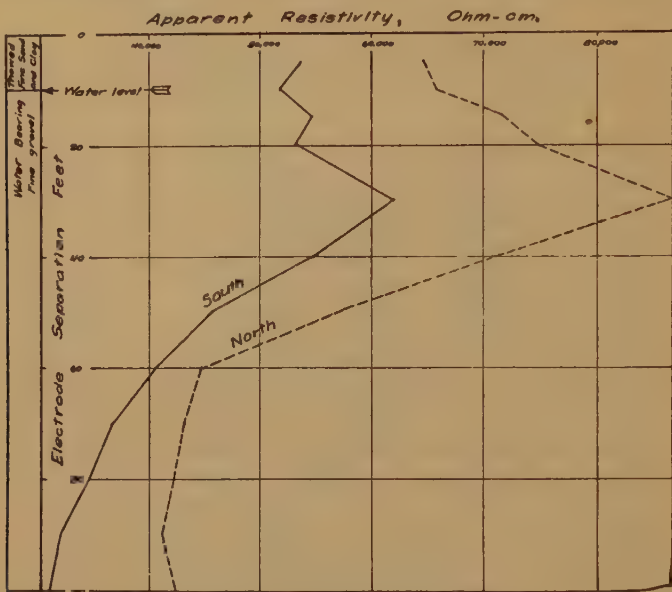

FIG. 20.—DEPTH PROFILE IN SHALLOW, WATER-BEARING GRAVEL, TANANA VALLEY, NEAR COLLEGE.

of several depth profiles taken over a gravel and silt-filled creek channel. The low surface resistivity is typical of thawed, wet silt, and the increased resistivity at greater depths is characteristic of thick water-bearing gravel beds. Low-resistivity bedrock at about 110 ft. is apparently indicated by the sharp drop at that electrode spacing, which coincides with the known depth of approximately 100 ft. The presence of abundant water was later confirmed by drilling.

Fig. 20 shows a depth profile run in July where the water level is at a shallow depth. A dry, sandy surface accounts for the high surface resistivities, while the high resistivity of the north line may be caused partly by a small mass of near-surface frost, formed in the shade of a building. Water at a depth of about 10 ft. is indicated by the south resistivity line; the actual water level was found to be 9 ft. below the

CONCLUSIONS

When supported by geological and mineralogical data, the magnetometric method is of value in preliminary prospecting for about half of the gold placers in interior Alaska. It is most successful where placers, containing sufficient magnetite, are concentrated in pay streaks. It is of no value in finding placers that contain insufficient magnetite or those with which large bedrock anomalies are associated. Although the magnetometric method cannot be used for evaluating placer ground, it often makes unnecessary much of the relatively slow and expensive drilling or shaft prospecting, particularly in barren areas.

Because of the great differences in resistivity between frozen and thawed material, the direct-current resistivity method offers a rapid and reliable means of determining the areal extent and ap-

proximate depth of permanently frozen unconsolidated deposits. Determinations of depths to bedrock were not entirely satisfactory, owing mainly to the frequent lack of lateral uniformity in the overburden and the bedrock.

Water-bearing deposits associated with permanently frozen ground can be indicated usually by locating thawed areas or strata. When the overburden is thawed, the presence of water can be determined under favorable conditions.

The Gish-Rooney empirical rule—which states that the depth to a discontinuity is equal to the electrode separation corresponding to the break in the resistivity-depth profile—was found to be of more general value than depth calculations based on theoretical considerations. The empirical rule usually held where high-resistivity surface layers were encountered, consequently measurements made during the late winter or early spring, when the surface resistivity is high and uniform, are more easily interpreted than those made during the late summer.

Acknowledgments

The author wishes to express his thanks to F. W. Lee and J. H. Swartz, of the Geophysical Branch of the U. S. Geological Survey, for invaluable assistance given preliminary to undertaking this investigation; to R. E. Gebhardt, Observer in charge at the Sitka Magnetic Observatory, for furnishing daily magnetograms and magnetic forecasts; and to J. B. Mertie, Jr., of the Alaska Branch of the U. S. Geological Survey, for supplying about 60 samples of placer concentrates. He is also indebted to Al Malden, Ernest Wolff and Erwin Clahassey, students or former students at the University of Alaska, for assistance in carrying out the work; and to the miners and prospectors, too numerous to mention by name, who cheerfully furnished hospitality when needed and information when requested.

References

1. J. C. Boswell: Application of Geomagnetics to Placer Exploration. Unpublished thesis submitted for B. S. in Mining and Geology, Univ. of Alaska, 1929.
2. T. Mathews: Application of Geo-resistivity to Placer Exploration. Unpublished thesis submitted for Bachelor of Mining Engineering, Univ. of Alaska, 1938.
3. P. S. Smith: Areal Geology of Alaska. U. S. Geol. Survey *Prof. Paper* 192 (1939) 66–72.
4. J. B. Mertie, Jr.: The Yukon-Tanana Region, Alaska. U. S. Geol. Survey *Bull.* 872 (1937) 183–198.
5. F. W. Lee: U. S. Bur. Mines *I. C.* 6899 (1936) 10–14.
6. F. W. Lee: U. S. Bur. Mines *I. C.* 6171 (1929).
7. F. Wenner: Nat. Bur. Stds. *Bull.* 258 (1916).
8. C. A. Heiland: Magnetometric Investigations of Placer Deposits near Golden, Colo. A.I.M.E., Geophysical Prospecting, 1929.
9. J. J. Jakosky and C. H. Wilson: Geophysical Studies in Placer and Water-supply Problems. A.I.M.E. *Tech. Pub.* 515 (1933).
10. D. Wantland: Comparison of Geophysical Surveys at the Roscoe Placer, Jefferson County, Colo. Colo. Sch. Mines *Quart.* (Jan. 1937) 32.
11. I. Roman: How to Compute Tables for Determining Electrical Resistivity of Underlying Beds and their Application to Geophysical Problems. U. S. Bur. Mines *Tech. Paper* 502 (1931).
12. I. Roman: Some Interpretations of Earth-resistivity Data. *Trans.* A.I.M.E. (1934).
13. E. Leffingwell: U. S. Geol. Survey *Prof. Paper* 109 (1919) 179–243. Discussion of frozen ground on northern coast of Alaska.

DISCUSSION

J. J. Jakosky presiding

J. W. Joyce* and D. G. Knapp.†—Dr. Joesting's paper is extremely interesting, particularly since it deals with physical conditions as encountered in northern latitudes, which in turn present problems in geophysical prospecting not encountered in temperate and southern latitudes.

In particular, the magnetic conditions encountered are typical of the auroral zone. It is characteristic of continuous records of the variations of the magnetic elements obtained at the Sitka Magnetic Observatory of the Coast and Geodetic Survey that on magnetically quiet days, except during the months from May to August, inclusive, the average diurnal variation of the vertical intensity is less than at observatories at lower latitudes. On the other hand, during magnetic disturbances, the ranges in the variations in Alaska are usually far greater than at lower latitudes. Thus, during quiet periods, diurnal variation

* Magnetic Observer, U. S. Coast and Geodetic Survey, Washington, D. C. Discussion approved for publication by the Director, U. S. Coast and Geodetic Survey.
† Junior Mathematician, U. S. Coast and Geodetic Survey.

control is relatively easy, while for disturbed interval it is practically impossible to attain.

Dr. Joesting has rightly recognized the fact that magnetograms from the Sitka observatory cannot be used to determine diurnal-variation corrections for vertical intensity at points in central or northern Alaska. Although much remains to be done on the study of diurnal variation of vertical intensity, enough is known to warrant skepticism regarding the validity of such corrections at sites more than 50 to 100 miles from the observatory. In northern areas, near to the auroral zone and the magnetic pole, it is likely that these limits may be reduced still more.

The problem of forecasting magnetic storms has received considerable attention in recent years. In the present state of our knowledge, it is not possible to predict with any great degree of certainty the occurrence of periods of magnetic disturbance, although by utilizing the 27-day recurrence phenomenon periods of probable disturbance may be indicated in a general way. A study of observatory records over many sun-spot cycles has indicated the existence of a quasi-periodicity of 27 days in the occurrence of many magnetic disturbances. This is approximately the period of the sun's rotation on its axis. If marked disturbance was observed 27 days ago and again today, this is not necessarily an indication that the same thing will occur 27 days hence, but the probability of such an occurrence is certainly higher than if the two previous solar rotations had shown quiet conditions at the time in question. The likelihood of another disturbance is problematical in a given instance, as some disturbances may recur with every rotation throughout a season while others recur only once or twice or not at all, and no method is known for estimating how many recurrences are likely of a given disturbance. Some of the most severe magnetic storms do not have any counterparts in previous or subsequent rotations. Furthermore, there is nothing to indicate when new disturbance cycles may be introduced bearing random phase relationships to former disturbances.

There is also some correlation between sun-spot positions and the occurrence of magnetic disturbances, but here again experience has indicated that the degree of success attained in such predictions is not sufficient to justify their use in making hard and fast rules regarding the conduct of magnetic surveys.

Using the observatory data as Dr. Joesting has used it, there is no doubt that certain disturbed periods were anticipated in a general way, but it must be emphasized that this procedure is not infallible, and that it is not capable of taking into account all of the factors involved. In the final analysis, for the present we can guarantee the occurrence of a period of magnetic disturbance only when we actually observe such a disturbance to be in progress.

TABLE 4.—*Three-hour-range Index*

Three-hour-range Index	Upper Limit of Disturbance Range, Gammas		
	Sitka	Cheltenham	Tucson
0	10	5	4
1	20	10	8
2	40	20	16
3	80	40	30
4	140	70	50
5	240	120	85
6	400	200	140
7	660	330	230
8	1000	500	350
9	>1000	>500	>350

The new measure of magnetic disturbance,* known as the three-hour-range index, may be of considerable use to the geophysical observer, in that it will permit him to obtain certain information regarding disturbance without having recourse to actual magnetograms or their reproductions. Starting with the hour corresponding to Greenwich midnight at the observatory, the day is divided into eight 3-hr. intervals. For each of these intervals, a number is assigned, which depicts the range of the element during the 3 hr, omitting the normal diurnal variation. Thus, the figure becomes a measure of disturbance. A scale of 10 units is employed; namely, 0, 1, 2–8, and 9. Each unit corresponds to a definite range for the 3-hr. interval, expressed in gammas (one gamma equals 10^{-5} oersteds), and the scale for any given observatory is determined in advance. In practice, it is usual to investigate the three elements ordinarily recorded—declination, horizontal intensity, and vertical

* J. Bartels, N. H. Heck and H. F. Johnston: The Three-Hour-Range Index Measuring Geomagnetic Activity. *Jnl. Terrestrial Magnetism and Atmospheric Electricity* (Dec. 1939) 44 (4).

intensity—and then give for the period the maximum number, without regard to which element it was derived from. For special work, such as geophysical prospecting, it would be possible to specify the index numbers for vertical intensity alone, or if desired, horizontal intensity alone. Thus, by giving a series of eight integers, an approximate idea of magnetic conditions for a complete 24-hr. period could be obtained. At Sitka, Cheltenham, and Tucson, for example, the three-hour-range index scales for all three elements are as shown in Table 4.

H. R. Joesting (author's reply).—Dr. Joyce is quite right about not being able to forecast magnetic conditions with any great degree of certainty. I think he wrote that discussion partly to make sure that other persons would not send for forecasts and expect them to be hard and fast guarantees of magnetic conditions.

S. F. Kelly*.—I have a question to raise about the curves for resistivity depth determination on pages 78 and 79, Figs. 12 and 13. The bedrock gives an extremely low resistivity, comparatively speaking, and I wonder if, under those circumstances the electrical-resistivity curve could be used to indicate the depth to bedrock, even though it underlies thawed sand and gravel.

H. R. Joesting.—These depths are depths obtained from a near-by water well 150 to 200 ft. away. I have no data on the actual depth to thawed material and to bedrock where the line was run. I do know that the depth of frost is greater immediately under the resistivity lines. I simply used the data that I actually had for the well. Probably if a well were drilled near the resistivity lines, we would find somewhat greater depths, but I am not at all certain of that.

S. F. Kelly.—In other words, that column at the left does not necessarily indicate the conditions shown in the curve.

H. R. Joesting.—No, it does not, and in view of the lenticularity and the irregularity of some of these frozen deposits, perhaps I should have explained more about that.

The same holds for Fig. 13. We took our resistivity data as close as possible to the drilled well. Incidentally, we took the data first and got our well logs after we had made our interpretations.

Of course the depth of thawed ground is shown rather well in view of the lenticularity both of the river deposits and of the frozen zones in them. There are no drill records of the depth to bedrock.

S. F. Kelly.—Your electrical measurements certainly went out far enough to produce adequate penetration into bedrock, and in all probability at the site where you were working bedrock had a lower resistivity than the thawed sand and gravel.

H. R. Joesting.—Yes, it did. This is in line with the usual resistivity of the rather soft mica schist bedrock in much of that area.

* Geophysical Services, Inc., Wilmington, Delaware.

Earth Resistivity as Applied to Problems of Exploration in the Potash-bearing Region near Carlsbad, New Mexico

By H. Cecil Spicer*

(New York Meeting, February 1941)

The results described in this article are based on field work conducted during the periods April–May, 1939, and May–July, 1940. The United States Potash Co. is mining potash on Government land under a permit from the Department of the Interior and the geophysical investigation was completed under a cooperative arrangement made between that company and the Conservation Branch of the Geological Survey. The writer, a member of the Section of Chemistry and Physics of the Geologic Branch, was assigned to this investigation.

Four definite objectives were in mind for the geophysical work in the studies over the salt deposits. The first was to determine the measure of success that could be attained in this type of work with the resistivity methods that were to be employed. These methods had been introduced into the work of the Conservation Branch by Benjamin E. Jones for the investigation of dam sites, and have been used under his direction by the author for such work.

If the method proved to be applicable, an effort was to be made to contour the top of the salt beds and also the other formation boundaries known to be present in this area. Salt-water aquifers were to be studied in an effort to determine their boundaries, and an attempt was to be made to delineate the potash-bearing beds.

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* U. S. Geological Survey, Washington, D. C.

Earlier Studies

Others have made, and reported, resistivity studies over saliferous deposits in different areas. Friedel[1] and Messrs. Schlumberger[2] reported geophysical work performed in the discovery of the salt domes of Alsace; Carrette and Kelly[3] described the geology of the same area. Leonardon and Kelly[4] published a resistivity curve obtained over the Hettenschlag dome, and a further discussion of this same area was given by the Messrs. Schlumberger[5] in a communication. Messrs. Alty[6] described studies on salt deposits in which the single-probe method was used. Siñerez[7] mentions that electrical methods were tried over salt deposits in Spain. Geoffrey and Charrin[8] show a resistivity curve obtained over marl, gypsiferous marl and salt which is similar to that obtained over the New Mexico salt deposits. Kelly[9] reported resistivity work performed with the ground comparator of Zuschlag over the salt deposits near Syracuse, N. Y., where the Salina formation is at a depth of 700 to 800 ft. Some structural studies on the potash basin of Alsace are described by Poldini.[10] Another single-probe resistivity study, made over salt deposits in New Mexico, is briefly described by Heiland,[11] through the courtesy of Harry Aurand, of the Midwest Refining Co.

Geological Features of Area Covered

The area discussed in this paper is in Eddy County, southeastern New Mexico, a

[1] References are at the end of the paper.

few miles east of Carlsbad. An interesting discussion of the search for, discovery and development of potash in this region is given by Smith,[12] whose article also contains remarks on the geological history of the salt-bearing beds. The resistivity observations were obtained in the Permian Basin near its southern end, close to the northwestern edge of the structural feature that is called the Delaware Basin (Fig. 1).

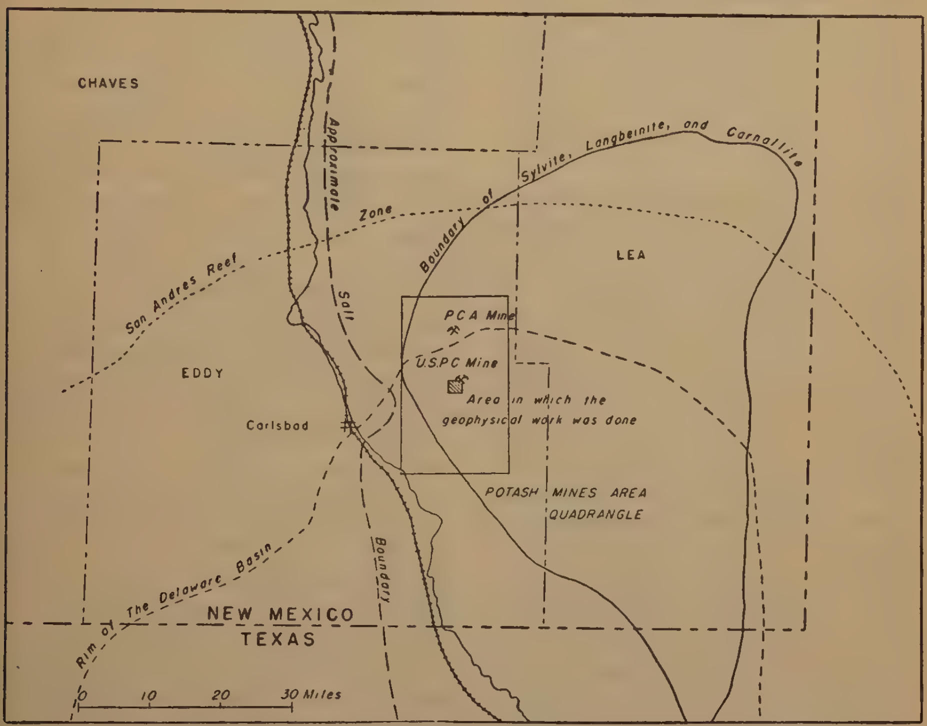

FIG. 1.—PORTION OF SOUTHERN END OF PERMIAN BASIN, SOUTHEASTERN NEW MEXICO, SHOWING POTASH AREA AND AREA IN WHICH GEOPHYSICAL WORK WAS DONE.

The main geologic features of the region have been presented by Lang[13] and references to previous studies that others have published on the area are also given by him. Only a brief description, therefore, will be given here of the geology pertinent to the area in which the resistivity studies were made.

The eastern portion of the area over which measurements were taken has very little relief, perhaps not more than 20 ft. Near the middle of the area there is a ridge, which rises to about 100 ft. above the eastern part. Westward from the summit of the ridge, the surface dips gently to form a gully. Beyond this gully, the surface again rises about 50 ft. to a height less than that on the eastern side. From this point westward, the surface slopes gently downward toward the Pecos River.

The rocks in the area are of Quaternary, Triassic, and Permian age. The surface is covered with dune sands. The Quaternary deposits (40 to 250 ft. thick) are composed of caliche, cobbles of limestone, gypsum, and sandstone, boulders, sands, and some fine clayey material. The Triassic rocks (140 to more than 275 ft. thick) are the familiar red beds, consisting of sands, clays, and mixtures of the two materials.

The Permian rocks are made up of two main parts insofar as the present resistivity observations are concerned. The upper part, or Rustler formation (200 to 400+ ft. thick) is composed of gypsum, anhydrite, dolomitic limestone, shale, and some sand and clay. The next lower part is the Salado formation, which is the salt layer and contains halite, polyhalite, some clays and the richer potassium salts—sylvite, carnallite and langbeinite.

Earlier geological studies and the correlation of various drill logs had indicated that the truncated salt surface existed in the western part of this area. All the studies, however, have assumed that the attitude of the beds coincides approximately with the surface that is indicated by joining the drilled depths to salt.

The measurements were made with the Gish-Rooney earth-resistivity apparatus, which was modified to contain some features that were found in practice to be necessary to obtain consistent results. A potential cable was made up of low-impedance shielded microphone cable and shielded three-way plugs, which fitted into matching jacks. The shield of the cable was connected to the plug case, which was grounded by contact with a small flat spring mounted at the side of the jack opening. In order to reduce any other stray potentials within the instrument, all current leads were shielded and the shields were connected to ground. A grounded shield or guard ring was placed between the current and potential drums of the commutator. All brushes of the commutator that were on interrupted circuits were changed to a bent-end type, which gave smoother commutation and permitted very close adjustment. Furthermore, arcing and the attendant burning of the segments was greatly reduced, even with the continuous use of voltages above three hundred.

Single conductor, rubber-covered wire was used for carrying current and potential. This was wound on duralumin (ST17) reels, and connection of the wire to the instrument was made through a specially designed slip ring and brush mounted on the side of the reel. Heavy copper-clad steel stakes were used as electrodes.

As a power supply, 45-volt extra-heavy-duty radio B batteries were connected in series parallel. These were placed in a box and connected to a selector switch, so that voltages from 0 to 450 by 22½-volt steps were available. With two units in parallel these batteries gave remarkable service under an intermittent drain of 0.3 to 0.5 ampere.

The modification of the Wenner arrangement of electrodes as proposed by F. W. Lee was used in all of the measurements. The electrode intervals were expanded outward from the central stake, so that vertical electrical drilling results were obtained. The apparent resistivity was computed from the formula $\rho = 2\pi a \frac{E}{I}$ in which a = electrode interval, E = voltage across potential electrodes, and I = the current flowing through the earth. Curves of apparent resistivity were then plotted with the computed resistivity values and electrode spacings as coordinates. Resistivity mapping was not used in this work because of the large and unexpected variation of apparent resistivity that was found to exist in the same formation within short distances.

Most of the preliminary resistivity work done during the first season was restricted to taking observations near the drill holes of the area and correlating the interpretations from the curves with the logs available for these holes. Some of these resistivity curves are shown in conjunction with the drilling log in Fig. 2. They are all of the same general type; in fact, all of the curves except one that were obtained during both seasons of work were of this same type.

After the preliminary curves and their interpretations were completed, a series of

widely spaced resistivity lines was obtained in the westerly area beyond drill hole No. 3, where the salt layer is truncated. The interpretation of these curves definitely depth to salt was found by the preliminary work.

The later studies were made to check this very unexpected dip in the salt more care-

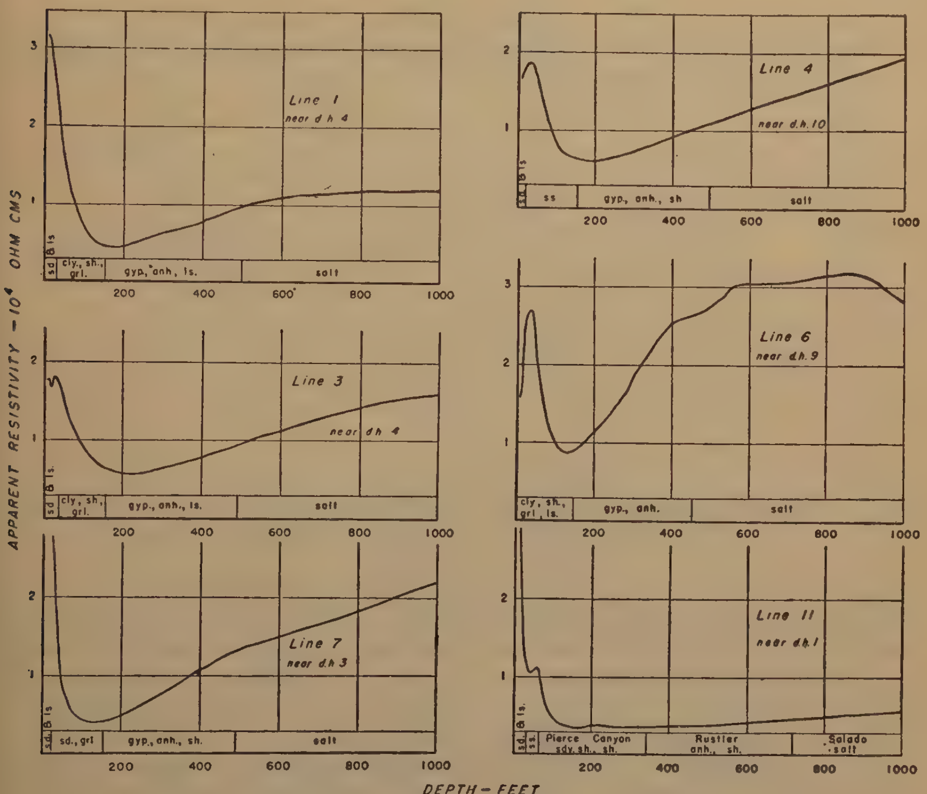

FIG. 2.—SOME PRELIMINARY RESISTIVITY CURVES AND NEAR-BY DRILL LOGS.

indicated that the surface of the truncated salt layer did not slope uniformly downward between drill holes No. 3 and No. 1, as had been predicted by the earlier geological studies and drilling logs. Instead, it was estimated from the geophysical interpretations that the top of the salt layer descended rapidly from a point somewhat west of drill hole No. 3 to a depth greater than had been found by drilling at hole No. 1, and then rose again to the elevation found in the latter drill hole. Insofar as observations were obtainable west of drill hole No. 1, no other unexpected fully both geophysically and geologically. A closely spaced series of apparent resistivity curves was obtained between lines No. 7 and No. 9-9*A* of the earlier work. The later resistivity lines were arranged in order to determine more carefully the depths to salt, and to determine a desirable location for drill hole No. 2. The geophysical field work was completed before the drill hole reached the lower formations and because of this delay the interpretations of the resistivity curves were revised subsequent to the completion of the well

to correspond with the resistivity conditions found to obtain near by.

As it is not possible to present in a limited space all of the apparent resistivity curves that were obtained during this work, only the features of most interest are described. The interpreted results have been reduced to drawings that show the subsurface conditions.

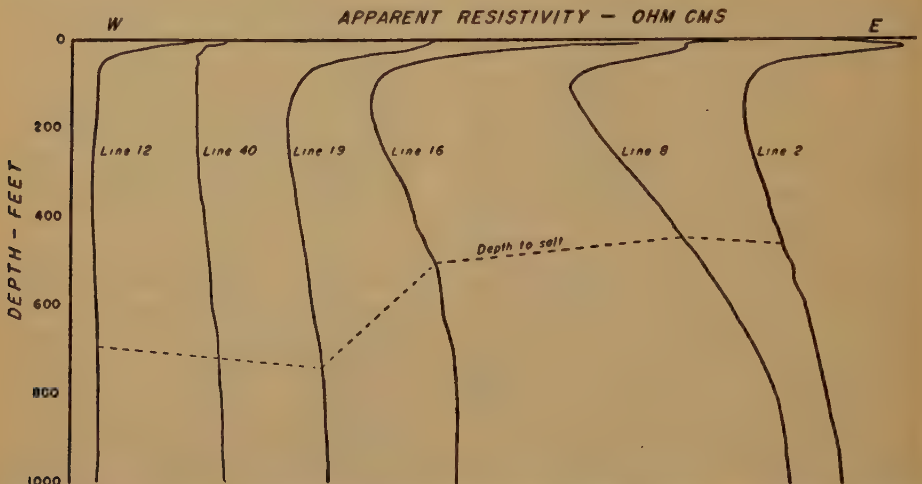

FIG. 3.—VARIATION OF APPARENT RESISTIVITY FROM WEST TO EAST ACROSS AREA. EFFECT OF SALT LAYER AND ITS VARIATION WITH DEPTH ALSO ARE SHOWN.

The curves of Figs. 2 and 3 illustrate the similarity of the resistivity curves. Those of Fig. 3 particularly show the variation in apparent resistance of the layers from west to east across the area. The effect on the curves produced by the salt layer and the variation in depth of this layer to the west are shown in the diagram.

Cross sections delineating the main formation boundaries as determined geophysically are shown to scale in Fig. 4. Each section represents the results of a series of observations completed along a line parallel to the imaginary one joining the drill holes No. 2 and No. 3. All of the sections are in the area in which the salt layer is truncated. The revised geological and geophysical estimates of the formation boundaries are also shown in section *D* of Fig. 4. Both of these estimates are correlated with the log of drill hole No. 2. The geological estimate was made by joining recognized or expected depths to formation boundaries, whereas the geophysical estimate was made by joining the interpreted depths to changes in formations.

The configuration of electrodes used gives a series of three resistivity curves, two of which portray the effects of subsurface conditions between the center (ground) stake and each potential stake; while the third indicates the subsurface conditions between the two outside potential electrodes. The interpretations of depth to the formations from all of these apparent resistivity curves have been reduced to maps that show the structural contours drawn on the tops of the Salado and Rustler formations (Figs. 5 and 6). The surface topography for the same area is shown in Fig. 7, taken from the preliminary map of the potash area published by the Geological Survey.

A comparative study of the drill log for test hole No. 2 and the interpretations of resistivity line 40 of Fig. 3 indicates the effect on the curves of the saline water

found in the dolomitic member of the Rustler formation. From this known point, it was possible to extend the interpretations of the effect of the salt water to the other were found to be well adapted to this type of work; especially when geological information from correctly positioned drill holes was available for reference. Some difficulties

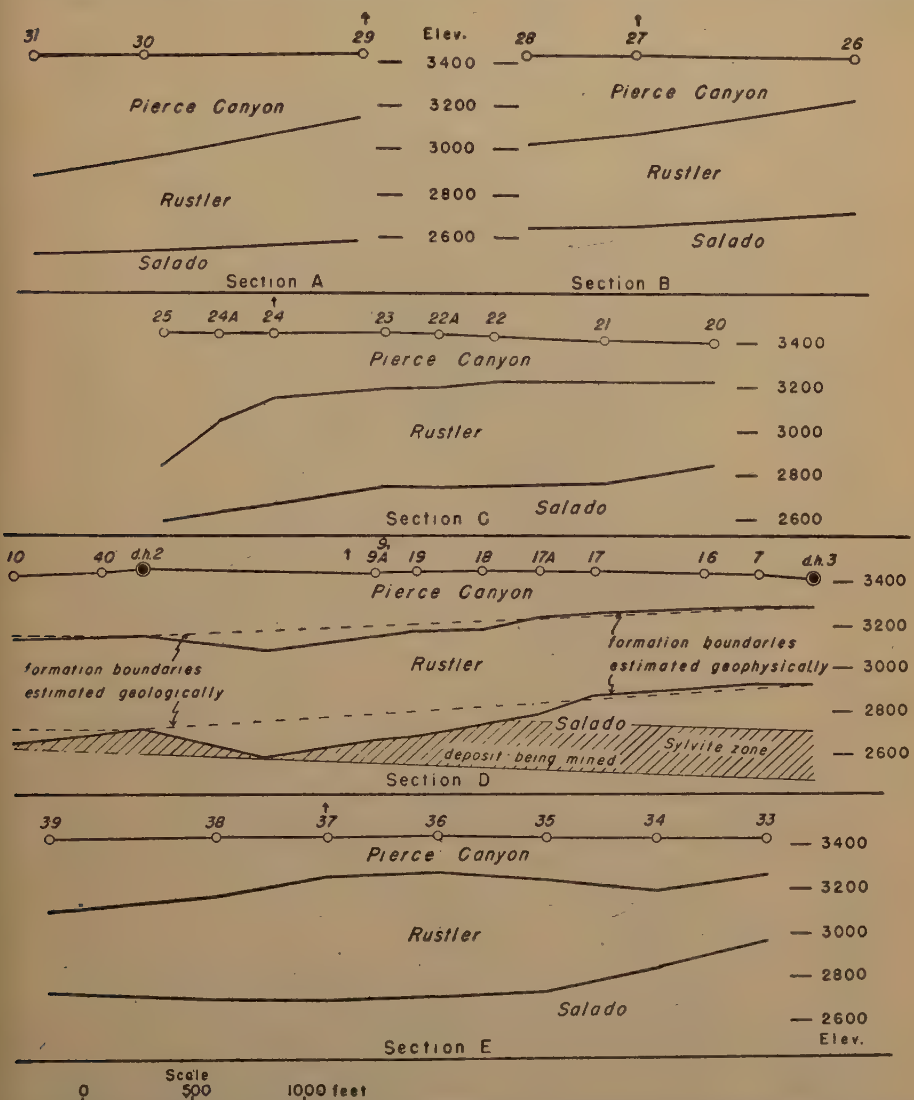

FIG. 4.—SW-NE CROSS SECTIONS SHOWING GEOPHYSICALLY DETERMINED BOUNDARIES OF FORMATIONS IN AREA. ARROWS INDICATE COMMON NORTH LINE.

apparent resistivity curves. The estimated eastern boundary of the salt water is shown on the surface topography map of Fig. 7.

The resistivity methods, on the whole, were encountered, as had been expected, at places where the Pierce Canyon redbeds were unusually thick. This formation has a very low resistance, and in greatly thick-

ened layers tends to blanket the effects of the lower, more resistant beds. Under the more favorable stratigraphic conditions, no difficulty was experienced in obtaining measurements at a 1000-ft. electrode in close agreement with the interpreted values from the apparent resistivity curves obtained close by. In consequence, it is felt that the results reliably depict the formation boundaries in the area investigated.

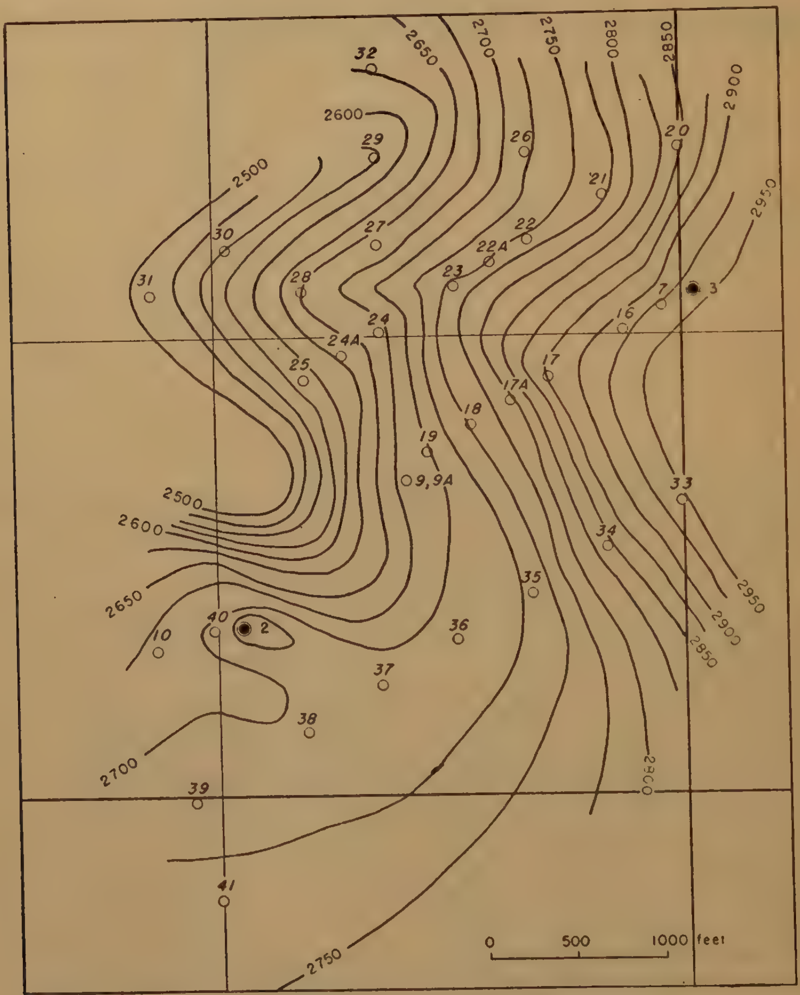

FIG. 5.—CONTOURS ON TOP OF SALADO FORMATION.

interval. If the apparatus had not been physically limited in some respects, much greater electrode spreads could have been used at some places in order to penetrate to greater depths.

The depths to the main formations known by drilling were, for the most part,

The sunken area in the salt (Fig. 5), which is reflected in the Rustler formation (Fig. 6) and to a certain extent in the surface features (Fig. 7), seems to be related to the history of geological events in the area at the time the lower beds were tilted, or else closely subsequent thereto. The main

reason offered for the support of this suggestion is the decrease in apparent resistance of the Rustler formation to the west of drill hole No. 3. To the east of this cracks were filled in with materials of lower resistance from above; and possibly some salt water invaded the formation from below. In this manner, the resistance

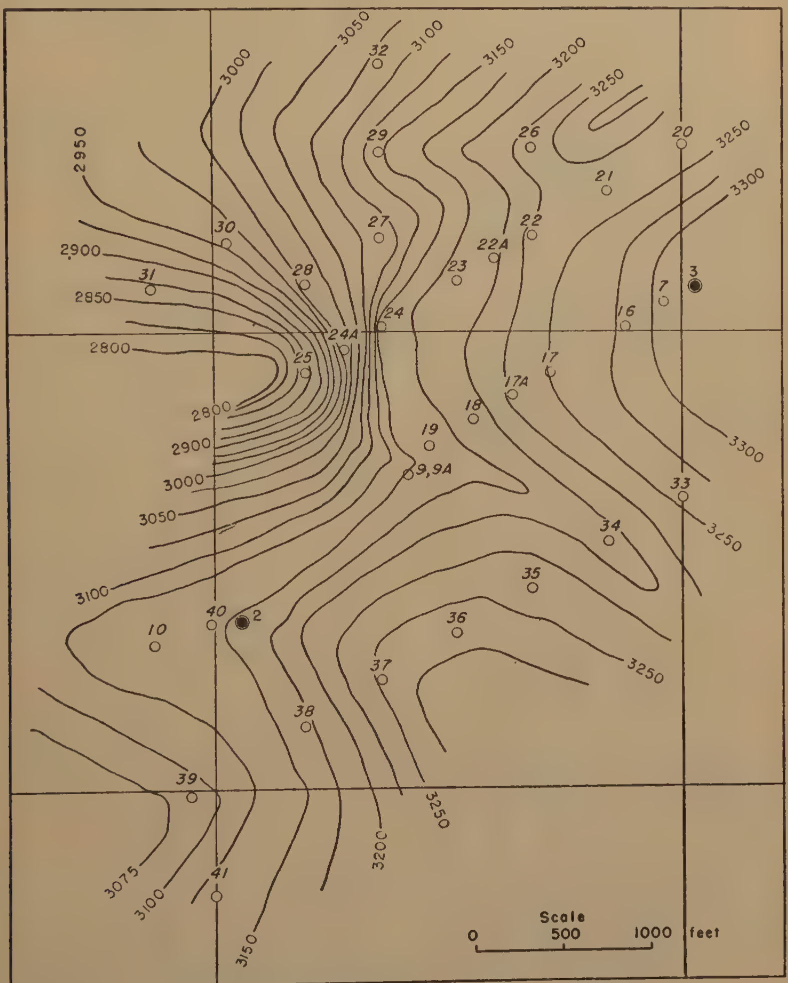

FIG. 6.—CONTOURS ON TOP OF RUSTLER FORMATION.

location, the formation had a resistance of 150,000 to 220,000 ohm-cm.; but decreased to about one-fourth of this value westward. In order to explain this condition, it is suggested that the upper salt has been removed by solution, thus causing the adjacent upper formations to fracture and settle into the depression formed. The of the formation may have been lowered. No water was reported in drill holes 1 or 3, and it appears favorable to this suggestion that the saline water found in test hole No. 2 may possibly have been in some manner associated with the proposed fractured and depressed subsurface area. If a careful study of the samples from all

the drill holes had been possible, it might have verified this predicted condition; but only drillers' logs are available for test holes 1 and 3.

where such water was known to be present in the formations. Location of the fresher waters in the area, then, is dependent mainly upon the correlation of known

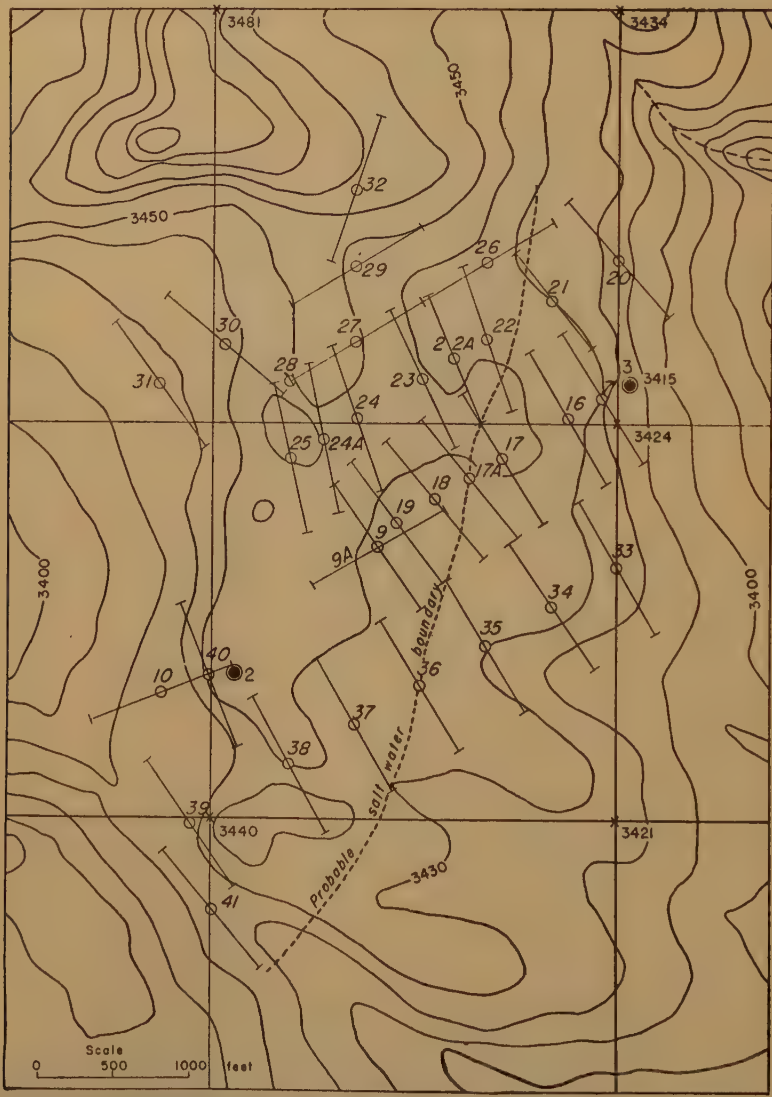

FIG. 7.—SURFACE TOPOGRAPHY, LOCATION OF DRILL HOLES, RESISTIVITY LINE CENTERS AND DIRECTIONS OF LINES, AND PROBABLE EASTERN BOUNDARY OF SALT WATER.

The salt-water boundary is believed to have been closely defined by the resistivity studies insofar as observations were completed. Potable water made no definite alteration on the curves taken in a place

gelogical results and interpretations from observations of electrical resistivity.

The potash deposits are very thin in comparison with the thickness of the salt in which they are found, and, too, they

contain included salt as well as other materials. A freshly opened and quite dry potash face when tested had a resistance of 359,000 ohm-cm. whereas a freshly opened and slightly moist salt face had a resistance of only 4940 ohm-cm. Even though this is definitely a very large change in resistance, no certain effect that could be attributed to the potash was ascertainable on any of the resistivity curves obtained by the method in use.

In the limited area studied, the geophysical picture does not closely correlate with the expected geological picture in that the subsurface structures are not strongly reflected in the ground surface. This can be attributed, perhaps, to the fact that the geological relation is a generalization whereas the geophysical study reveals a detailed structural variation in the area.

The results of the geophysical study should be helpful in serving as a guide to mining operations should they ever be extended toward this area.

The splendid cooperation of the United States Potash Co. in providing assistants, a field truck, numerous incidental repairs to equipment, the drilling of a test hole, and the identification of the sample log by its geologist, is acknowledged with appreciation.

Summary

Results are described of resistivity observations made over the potash-bearing formation in southeastern New Mexico and obtained with the Gish-Rooney apparatus. The salt (Salado) and Rustler formations were contoured and aquifers were studied in relation to possible flooding of mines. Potash beds made no alteration on the resistivity curves.

References

1. G. Friedel: Sur l'existence d'un dôme de sel dans le basin potassique oligocène du Haut-Rhin. *Compt. rend.* (1927) **184** (18), 1028–1031.
2. C. and M. Schlumberger: Découverte près de Hettenschlag d'un deuxième dôme de sel sous la plaine d'Alsace. *Compt. rend.* (1927) **186** (7), 445–446.
3. G. Carrette and S. F. Kelly: Discovery of Salt Domes in Alsace by Electrical Exploration. *Trans.* A.I.M.E. (1929) **81**, 211–220. Geophysical Prospecting.
4. E. G. Leonardon and S. F. Kelly: Some Application of Potential Methods to Structural Studies. *Trans.* A.I.M.E. (1929) **81**, 192. Geophysical Prospecting.
5. C. and M. Schlumberger: La prospection électrique de basin salifère d'Alsace. Cong. Int. Min. Mét. Geol. appl., 7e session, Paris (1935) Geol. II, 855–864.
6. T. and S. Alty: Detection of Rock Salt by the Method of Electrical Prospecting. *Canadian Jnl. Research* (1930) **3** (6), 521–525.
7. J. G. Siñerez: Los metodos geofísicas de prospección. *Bull.* Inst. Geol. y Min. de España (1928).
8. P. Geoffroy and P. Charrin: Études géologiques et prospections minéras par les méthodes géophysiques. *Bull.* de service carte géologique de l'Algerie, Geophys. [4] (1932) No. 1, 147–148.
9. S. F. Kelly: Geophysics in the Metallic and Nonmetallic Fields. *Min. and Met.* (1934) **15**, 37–38.
10. E. M. Poldini: Les sondages électriques. *Bull. Technique de la Suise Romande* (1932).
11. C. A. Heiland: Advances in Technique and Application of Resistivity and Potential-drop-ratio Methods in Oil Prospecting. *Bull.* Amer. Assn. Petr. Geol. (1932) **16**, 1260–1336.
12. H. I. Smith: Potash in the Permian Salt Basin. *Ind. and Eng. Chem.* (1938) **30**, 854–860.
13. W. B. Lang: The Permian Formations of the Pecos Valley of New Mexico and Texas. *Bull.* Amer. Assn. Petr. Geol. (1937) **21**, 833–899.

The Magnetometer as a Geological Instrument at Sudbury

By F. McIntosh Galbraith,* Member A.I.M.E.

(New York Meeting, February 1942)

This paper describes the use of the magnetometer, under geological direction, in exploration of the Sudbury nickel district. The writer's experience at Falconbridge has led him to the belief that only through detailed work, and by careful correlation of both geological and geophysical results, can geophysical prospecting methods be applied successfully to mining exploration problems. It is hoped that the basic technique described in the paper will be found to have general application.

Introduction

Within the past 20 years, geophysical methods of prospecting have become solidly established in the field of petroleum exploration. They have not, however, been similarly adopted by the mining industry, although mining is a far older craft and should be the more advanced in its technique. While, therefore, it is almost a routine matter to have geophysical surveys performed in a new area being tested for oil, a new metal-mining district is usually teeming with prospectors and promoters long before the technical man appears on the scene. Even then, only the more primitive engineering methods are customary in the early stages of exploration.

Three factors are chiefly responsible for this situation. The first is the difference between oil pools and ore deposits in their geological modes of occurrence. While most of the known metallic ore bodies have been found outcropping at the surface, petroleum deposits are characteristically buried. This does not mean that all ore deposits outcrop, but neither does it mean that we should rely on "wildcatting" to discover blind ore bodies. The second factor is the relative scale of metallic lodes and accumulations of petroleum. In areal extent, a metal-bearing vein deposit is typically a much smaller geological feature than an oil pool. Presenting a narrower target, it requires closer shooting to score a direct hit. And finally, there is the need, in mining work, for close correlation of the known local geology with geophysical observations. This becomes of increasing importance as the size of the objective diminishes. A geophysical disturbance on a large enough scale will be detected under almost any circumstances and by almost any technique; without benefit of geology, however, the significance of a local anomaly may easily be misread.

Campaign at Sudbury

In the Sudbury nickel district of Canada, new deposits of nickel and copper have been discovered recently by magnetic methods, under geological supervision. A campaign of exploration, designed to encompass the district eventually, was set in motion in the spring of 1935. After six years, a new and important ore body has been discovered and its continuity established to 1000 ft. in depth; several areas have been eliminated; and a number of possibilities remain to be tested. This has been accomplished with the expenditure of less than $150,000—including the cost of all diamond drilling.

The responsibility for carrying out this campaign was entrusted by the company to its Geological Department, and the under-

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* Chief Geologist, Falconbridge Nickel Mines Limited, Falconbridge, Ont., Canada.

taking was begun on a modest scale. A geological field party was organized to begin reconnaissance mapping of the areas selected for initial investigation. To the conventional surveying equipment, consisting of plane table and telescopic alidade, was added a sensitive magnetometer. A geophysical survey had been performed by Hans Lundberg over the immediate mine property in 1934. The possibilities implied, if similar results could be combined with sound geology, were attractive enough to warrant an extension of the mapping program to include magnetic surveying. To this end, the company purchased a Hotchkiss Superdip. Before the mag-

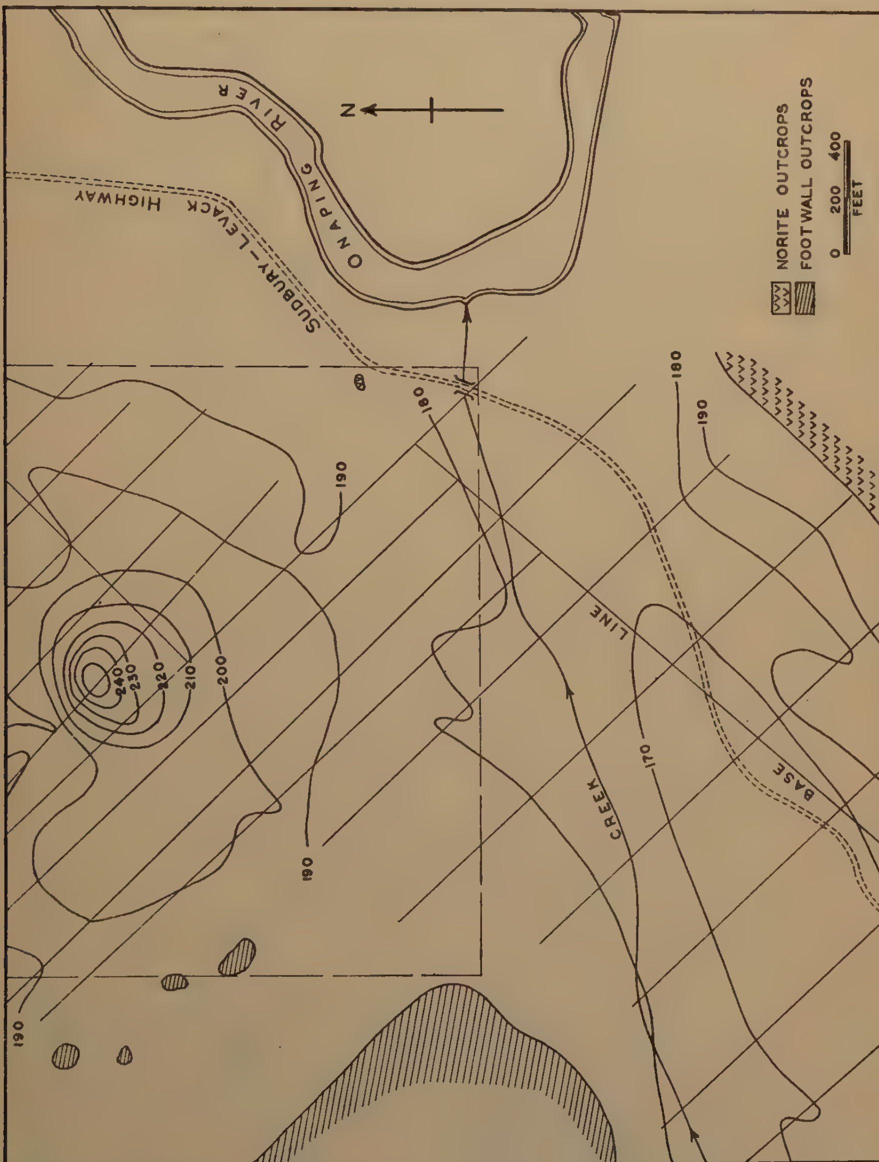

FIG. 1.—RECONNAISSANCE GEOLOGICAL MAP WITH MAGNETIC CONTOURS.

netometer was put into active service, however, experiments to test its behavior in the field under known conditions were conducted at the mine. A convenient practicable sensitivity was determined; and it was found that the instrument gave its best results oriented across the magnetic meridian, recording vertical intensities only.

Field procedure followed the usual pattern, except that magnetic surveying immediately preceded plane-table mapping of the area. The senior geologist first laid out a base line, to be picketed and taped, from which cross lines were laid out at right angles. The magnetometer was then set up to follow these lines, taking observations

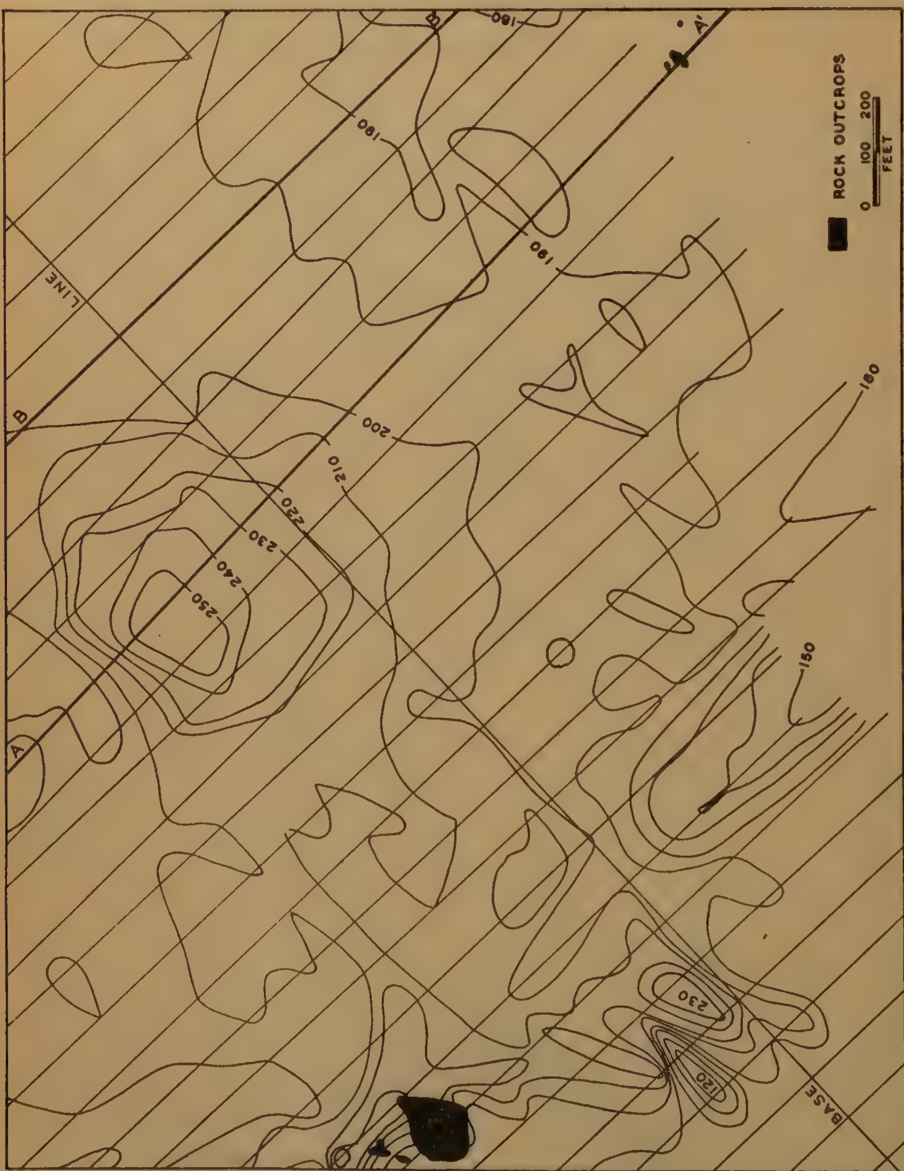

Fig. 2.—Detailed Map of Magnetic Anomaly.

at regular intervals. The plane table followed the magnetometer, recording the positions of the lines, and making a careful outcrop map of the surface geology. Topography was not contoured, although elevations were carried by the plane table so that profiles could be drawn along any of the magnetometer lines. The plane-table sheets were kept up to date every day; also the magnetic records. These were transferred to a special plan, on tracing vellum, that had the same scale as the geological map, so that an immediate comparison was always possible. Thus the inherent advantages of plane-table mapping were retained for the geological work, and were extended to cover the geophysical work.

The ore bodies in the Sudbury district are essentially deposits of massive sulphides, occurring at the outer norite contact, and of which the principal constituent is pyrrhotite.* The surface covering is chiefly glacial outwash, which is spread unevenly over the district; and the depth of covering varies between 50 and 300 ft., averaging perhaps 100 ft. Under these conditions, a scale of 1:4800 (400 ft. to the inch) was adopted for reconnaissance work, and proved quite satisfactory. An interval of 400 ft. was selected for the magnetic cross lines, and observations were taken every 100 ft. along these lines. Whenever the geophysical work showed anything interesting, or when the geological mapping seemed to call for it, intermediate lines were set off and traversed by the magnetometer.

As soon as the field work was completed in any given area, a comprehensive geological map was prepared in the office, showing surface geology, the location of all magnetometer lines, and any pertinent topographic or cultural features. A preliminary analysis of the magnetic results was made separately, vertical intensities were contoured, and magnetic profiles were drawn. A contour plan, representing vertical magnetic intensities, was then made on very thin tracing paper in the form of a cover sheet for the geological map. Thus either plan could be viewed by itself or, by superposition, both could be studied at the same time together.

The conditions under which the discovery of ore in Levack township was made have been described in a previous paper,[1] and will not be considered here. Selected maps and cross sections, however, illustrating both the technique applied and the results obtained, are presented herewith to tell their own story.

Fig. 1, transcribed from our original reconnaissance map, shows the immediate vicinity of the ore body. The buried outcrop of this deposit was found by diamond drilling beneath the magnetic anomaly outlined on the map, and the discovery hole went through 138 ft. of sand and gravel before intersecting the ore at bedrock. The magnetic contours are plotted in terms of scale division readings of the Hotchkiss instrument* and, on the original map, were shown on a separate cover sheet. The disposition of the magnetometer lines is shown exactly as they were surveyed by the plane table. As the map suggests, reconnaissance was directed primarily at covering the area with all the speed consistent with thoroughness. The area covered by Fig. 2 is indicated in dashed outlines.

Fig. 2 shows the significant portion of the same area in much greater detail.

* Probably of equal importance in any magnetic investigation is the very small but universal percentage of magnetite in the ores.

[1] F. M. Galbraith and R. C. Hart: Geophysics in Exploration at Falconbridge. *Trans.* Canadian Inst. Min. and Met. (1939) **42**, 527–531.

* The sensitivity at which the Superdip was operated is difficult to define accurately in simple terms. Because of the mechanics of the instrument, the number of gammas measured by one scale division varies directly with the intensity of the magnetic force being recorded; and a curve would be required to show the range of values for any given setting. In this instance, the approximate range is between 15 and 35 gammas per instrument scale division.

This work was done following the discovery of ore and in preparation for its intensive development. The picture has not been materially changed in perspective, although closer work has filled in the foreground and middle distance with an immense amount of valuable detail. The scale of the map was increased 10 times for this study, and both the spacing between lines and the interval between magnetic observations were cut in two. The topography was carefully contoured at 10-ft.

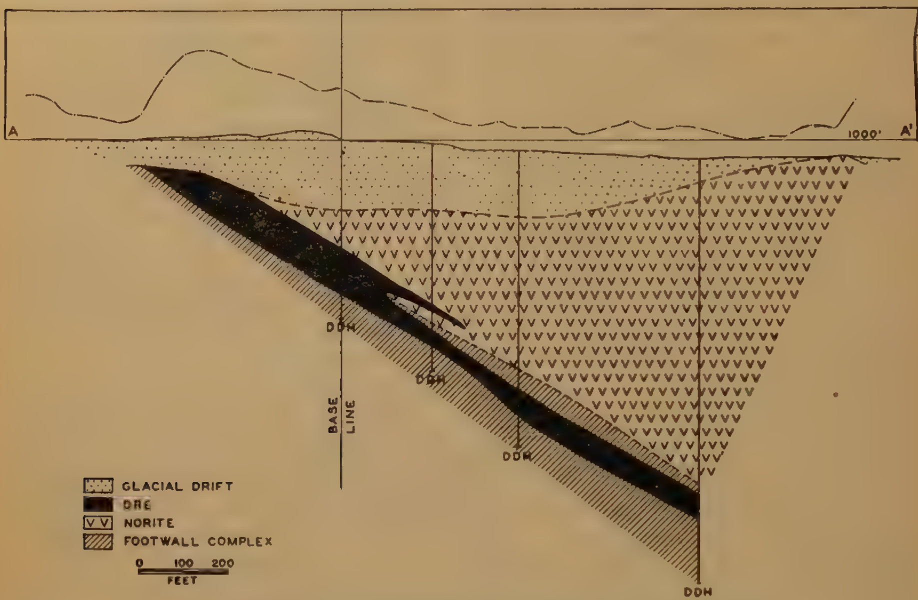

FIG. 3.—GEOLOGICAL CROSS SECTION AA′ WITH MAGNETIC PROFILE.

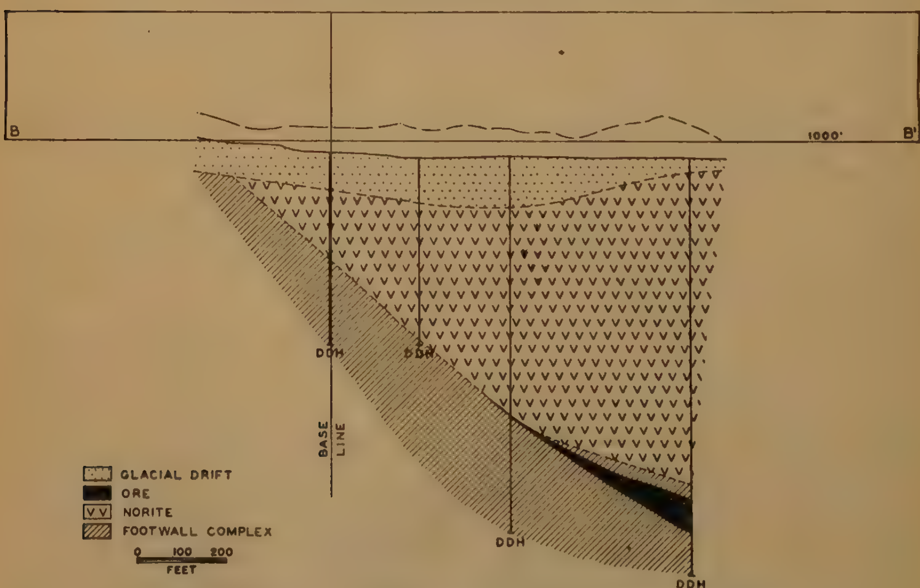

FIG. 4.—GEOLOGICAL CROSS SECTION BB′ WITH MAGNETIC PROFILE.

intervals but could not be conveniently depicted here. AA' and BB' are lines along which the cross sections shown in Figs. 3 and 4 were drawn.

Fig. 3 is a cross section, looking northeast, along AA'. The significant points to be noted are the position of the magnetic anomaly in relation to the ore body, and the shape of the curve. The magnetic peak can be seen to lie directly above the buried outcrop of the ore body. Measuring vertical intensities only, there is no tendency for the peak to be displaced to the north by the influence of the horizontal component. This is of definite practical value, since the peak of resultant intensity (measured in the magnetic meridian) occurs about 100 ft. farther to the northwest. The slope of the curve indicates very strikingly the dip of the ore body. Contrary to certain textbook illustrations, the upper pole of this gigantic magnet dominates completely, leaving no visible effect of attraction by the lower pole. Its attitude is reflected by the abrupt drop in the profile at the footwall side of the ore body, and by the longer gentle slope over the hanging wall. This corresponds to the theoretical effect of an equivalent magnet having infinite length.

Fig. 4 was drawn along BB', and is noteworthy because it implies that much deeper exploration is possible with the magnetometer than had at first been visualized. Early experiments at Falconbridge suggested that possibly 400 ft. would be the maximum depth from which magnetic observations could be expected to yield reliable indications in the Sudbury district. The ore intersected by the deepest hole shown on this section, however, is 750 ft. below the surface; and while the magnetic anomaly above it is feeble in intensity, it is distinct and regular in character. This suggests that, under certain conditions, some measure of reliance can be placed upon comparatively weak anomalies such as this. Only by dint of careful detailed work, however, will it be possible to recognize such indications, not to speak of interpreting them correctly.

Conclusions

The conclusions to which experience at Falconbridge has led can be simply and briefly stated. The magnetometer can be, and is being, successfully used for exploration in the Sudbury district. The work is carried on under geological direction as a supplement to normal geological activities. This is sound practice for mining exploration, since ultimately the results of geophysical work must be interpreted in terms of geology. In fact, the use of any form of geophysics is merely an attempt to extend our geological knowledge beyond the limits of the visible outcrops.

A background of empirical observation is of prime importance in the interpretation of magnetic measurements. While laboratory experiments are essential to the advancement of geophysics, their immediate results should be treated with extreme caution. The rigid control of experimental conditions, so necessary for research, is never realized and only rarely approximated in the field. A massive igneous rock, like the Sudbury norite, for example, may be homogeneous compared to the variety of rock types surrounding it; but it is far from being uniform in a strict physical or chemical sense. Theoretical principles therefore must be drawn upon *only* as they are found by experience to apply to particular field conditions.

Since the magnetometer has proved such an effective geological implement at Sudbury, similar results in other localities may reasonably be expected. The peculiarly favorable set of conditions existing in the Sudbury district will be hard to duplicate elsewhere, no doubt. Nevertheless, the technique is capable of almost universal application; and it is this writer's opinion that the geological approach illustrated by this paper offers the only real hope of applying geophysics successfully to problems of mining exploration.

DISCUSSION

(*Donald H. McLaughlin presiding*)

S. F. Kelly.*—I should like to ask Mr. Galbraith whether or not they have found themselves led astray in their magnetic exploration by detecting magnetic highs that subsequently proved to be due either to basic igneous rocks, or to disseminations of magnetite?

That question is raised by a specific example that came to my attention not long ago in western Canda, where magnetic exploration was carried out in the neighborhood of some known nickel deposits. A number of definite magnetic highs were observed. The smaller of these highs were drilled first and in each case found to correspond to nickel-bearing pyrrhotite, but low grade.

The company was then impelled by the success of this preliminary drilling campaign to omit the drilling of the largest and most distant of the magnetic highs. They were quite confident they were going to encounter a large nickel body, drove a long drift into the area of magnetic highs, and found that the magnetic anomalies were due to disseminated magnetite!

I have been informed by other operators in the east that they have often found that their magnetic highs corresponded not to pyrrhotite, but to basic rocks.

This illustrates very forcibly the necessity of applying as many geophysical methods to a given problem as will work thereon, and I return again to the same point I have emphasized in the past in connection with sulphide exploration—that when operating on pyrrhotite the wisest thing to do is to combine magnetic work with electrical.

There is no question that magnetic work is effective in finding pyrrhotite bodies. The spontaneous polarization method is particularly effective on sulphide bodies, irrespective of whether or not they are pyrrhotite. Combining the two methods then provides an excellent means of discrimination. A magnetic high without an electrical one indicates the presence of a basic igneous rock, or magnetite. An electrical high without a magnetic one means sulphides probably lacking in pyrrhotite. Where both the electrical and the magnetic highs correspond, you can be fairly confident that they are due to sulphide deposits carrying pyrrhotite. Therefore, I would like to ask whether or not Mr. Galbraith has been troubled by finding some of his magnetic highs are due to magnetite rather than pyrrhotite?

The second question I want to ask relates to the displacement of magnetic highs. The author shows a magnetic anomaly directly over the peak of the pyrrhotite body, although a magnetic high may frequently be displaced some distance from the peak of the causative body. Dr. Heiland referred in his talk to the magnetic map of the bauxite area in Arkansas, and I happen to know from my own magnetic, gravitational and seismic operations in that area in 1941, that sometimes those magnetic reactions are displaced as much as a half mile or a mile from the peaks of the syenite highs which, presumably, cause them.

I should therefore like to inquire of Mr. Galbraith whether he found, in his Sudbury work, that the peak of the magnetic high might, on occasion, be badly displaced from the top of the causative body due, presumably, to the polarization of the body?

F. M. Galbraith (author's reply).—To answer the first question: yes, there are all kinds of other things that will give just as good magnetic condition as an ore body, and frequently much better. A diabase that is full of primary magnetite, and probably carries only 1 or 2 per cent of it, will give an anomaly of two to three thousand gammas under 150 ft. of cover, and that is apt to be better than some of the smaller ore bodies will do. But that kind of thing can be picked up, in part anyway, by being careful to map both the geology and the geophysics accurately at the same time and get them correlated one with the other.

If I understood the other question—that is, whether we found it advisable to use an electrical method to check the magnetic work—we have done so several times, and in all the cases where we knew we had ore we got a very good check. In one particular place where we thought we had ore we got a very good anomaly, both electrical and magnetic, but when we drove holes we found nothing, so we do not know the answer to that.

* Sherwin F. Kelly Geophysical Services, Inc., Wilmington, Del.; Geophysical Explorations Ltd., Toronto, Ont., Canada.

S. F. KELLY.—What electrical method did you use, may I ask?

F. M. GALBRAITH.—Both a ratio graph survey and electromagnetic, and it was ultimately checked by porous pots, which did not show anything.

S. F. KELLY.—So the porous pots—that is, the spontaneous polarization method—were right?

F. M. GALBRAITH.—They were right.

S. F. KELLY.—That is the method I recommended above.

F. M. GALBRAITH.—As far as displacement of the peak goes, the only cases we know of definitely are places that we have drilled—and either have found or have not found ore. In any place where we have found ore the peak has always been pure vertical intensity and always has been right over the ore body. In other places where we did not find ore we still do not know what gave the indication, so we cannot answer the question.

S. F. KELLY.—That might presumably mean that the peak has been displaced from the body, and you have not yet drilled around it far enough to pick it up.

F. M. GALBRAITH.—It is a mathematical possibility, but judging from the experience we had with the others I am very doubtful. I do not think it is good enough to warrant the spending of money.

T. A. DODGE.*—Mr. Galbraith's very excellent paper will be most heartening to those geologists who look forward to the day when a geophysical instrument ceases to be regarded by mining men as a modernized divining rod. The description of the procedure followed at Sudbury brings out very forcefully a most important point in all geophysical work—that the interpretation of geophysical results must be based upon a thorough knowledge of the local geology.

In an Askania magnetometer survey of chalcopyrite-pyrrhotite lenses in the Blue Ridge of Virginia, made for The American Metal Company, Limited, in 1939, curves were obtained whose shape was almost identical with that shown in Fig. 3 of Mr. Galbraith's paper. The mineralized zone dipped at the same angle as shown for the Sudbury ore body, but it outcropped as a gossan in places, and its effective width was not much more than one tenth that of the latter. The purpose of the survey was to determine the locations along the zone of the stronger, wider mineralization, so that diamond-drill holes could be laid out to advantage. This purpose was fairly well met.

However, an interesting complication, due to the local geology, led at first to a wrong interpretation of the geophysical results. Certain curves were unusually high and sharp at the crest, suggesting greater width, stronger mineralization, or both. After making further traverses, it was observed that the curves with unusually high crests were very much more irregular than the others, and extreme troughs and peaks were not uncommon. Because of the rather weak magnetic pull of pyrrhotite in comparison with magnetite, the fact that magnetic attraction varies as the cube of the distance, and the occurrence on some curves of subsidiary crests lying beyond the footwall of the ore zone, it was suspected that small masses of magnetite might be present in the gossan. Careful search proved this to be true, although this mineral had not previously been noticed. Chunks of gossan with disseminated magnetite could be found in places in the soil along the line of outcrop and on the footwall side, which was downhill. Thus the anomalous crests were explained, and thereafter only smooth curves were relied upon to indicate the relative strength of the pyrrhotite body.

* Geologist, Anaconda Copper Mining Co., Bisbee, Arizona.

H. LUNDBERG.*—Mr. Galbraith should be highly complimented on both this outstanding accomplishment and the clear and unassuming way in which he has presented his results. This type of paper is badly needed, not only to convince the mining men that geophysics can be useful and of great aid in finding ore bodies but also to show that geophysics must be taken as an integrating part of the geological work.

Most papers presented to this Institute emphasize the mathematical and theoretical

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side of the methods or discuss some particular instrument. It tends to confuse the practical miner, who seeing formulas and discussions in highly technical language, throws up his hands and shys away from "Geophysics" as something too far above him. In reality, geophysics is so simple and its principles are applied so frequently in every day life, that any mining engineer or geologist should be able to do much geophysical work himself.

As Mr. Galbraith says, geophysics has proved itself beyond expectations in the oil regions, where many new oil fields have been found geophysically, yet in mining very few geophysical results have been reported. This is partly because in developing an ore body a long time is required to obtain sufficient information as to its shape and attitude, and so far, in very few instances, has it been possible to directly compare the geophysical predictions with an ore body actually discovered. Often papers dealing with geophysical prospecting for ore, therefore, are filled out with theoretical discussions of details that overshadow the limited amount of practical confirmation of the geophysical results.

For more than 25 years I have worked with geophysical methods exclusively and my work has been confined mostly to ore bodies. From my experience, I have reached the conclusion that working with ore bodies, mathematical and elaborate calculations have very little to do with the interpretation of the results. Theory and calculus are well justified while working out new methods, in building instruments and in the laboratory, but so many approximations must be applied and so many factors taken into account when making an interpretation that the accuracy and expression of the results in minute figures appears futile.

I most certainly agree with Mr. Galbraith that geophysical methods should be carried out in the closest coordination with the geological work. Only by frequent comparison of the geological and geophysical observations, and by estimating and studying the contrasts between normal and anomalous areas, can the best results be expected.

Working with magnetic methods is particularly favorable in Canada, since we have a steep dipping earth's magnetic field, so that in whatever direction the inclination anomalies are recorded, they occur vertically above the features causing them.

The Sudbury district is also particularly well suited for magnetic work, and while Mr. Galbraith's suggestion is a good one—that magnetic methods should be tried in other areas also—it should always be remembered that when using magnetic methods the orientation of the ore body in relation to the earth's field has a great deal to do with the shape of the curves, and furthermore, if we try these methods in the southern hemisphere or near the equator, the results and experience obtained in Canada cannot be applied directly.

It is interesting to note that the magnetic maximum on Fig. 3 is obtained over a point situated 100 to 200 ft. from the footwall at bedrock surface. This could be used to determine the length of the ore body in this profile line and, to judge from this figure, the likely length of the ore body should be between 1400 and 1600 ft. The fact that the magnetic high has been obtained over the upper end of an ore body situated 750 ft. from the surface is extremely interesting, and more detail work here ought to give very valuable information and also be of the greatest aid in future prospecting at great depth in the Sudbury area.

Spontaneous Polarization Surveys near Guddadarangavvanahalli, Chitaldrug, Mysore State, India

By M. B. Ramachandra Rao*

(New York Meeting, February 1943)

The spontaneous polarization surveys dealt with in this paper were carried out near Guddadarangavvanahalli (lat. 14° 17′ N.; long. 76° 24′ E.) in Chitaldrug district, which forms part of the Chitaldrug schist belt. The occurrence of gold, copper, lead and antimony ores has been noticed for several years but efforts to exploit them have been unsuccessful, therefore some spontaneous polarization surveys were made in the hope of finding indications of workable ore bodies.

The country examined has a rugged topography, with numerous hills on which there is little vegetation. The climate is generally dry, the average annual rainfall of the tract being about 25 in., of which 17 in. occurs during the southwest monsoon.

The geological formations of the area pertain to an ancient schistose series known as the Dharwar system (Archean). Locally, the rock formations have been divided into three series[1]—the chloritic series (or the Chitaldrug formation), the clay series (or the G.R. formation) and the trap series (or the Jogimardi trap).

The chloritic series includes a complex of altered ancient traps and volcanic agglomerates intermixed with some schists of sedimentary origin, all of which are highly metamorphosed. The lithological types of this series are mostly distinguishable as greenstone schists, calc-chloritic schists, slaty schists, ochery and calcareous mica-chlorite schists, with subordinate bands of secondary limestone.

The clay series (G.R. formation) is made up of shaly and argillistic schists, lithomargic clays, sandstones and brecciated ferruginous quartzites.

The Jogimardi trap is mostly of the nature of an epidiorite (hornblende diabase), which is distinctly intrusive in the form of large laccolithic and narrower dikelike masses. In addition to this trap, there are other minor intrusives such as the chalybitic trap, quartz porphyry and quartz reefs.

The topographical and geological features of the area are noted on the map of Fig. 1. The locations of some of the spontaneous polarization centers determined by the geophysical survey are indicated also.

Method of Survey and Apparatus Employed

The spontaneous polarization surveys were carried out in the manner recommended by the Imperial Geophysical Experimental Survey.[2] Preliminary reconnaissance was first carried out along a series of parallel traverse lines that were laid out over the area. The potential profiles obtained in these traverses were plotted* on a suitable scale and when any

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1 References are at the end of the paper.

* The I.G.E.S. system of plotting the profiles was followed. The American practice appears to be different. The shape of the curve in one becomes a reflection of the other, according to these two systems.

important or characteristic gradients were noticeable in these profiles, the ground in the neighborhood was investigated in greater detail to determine the distribution

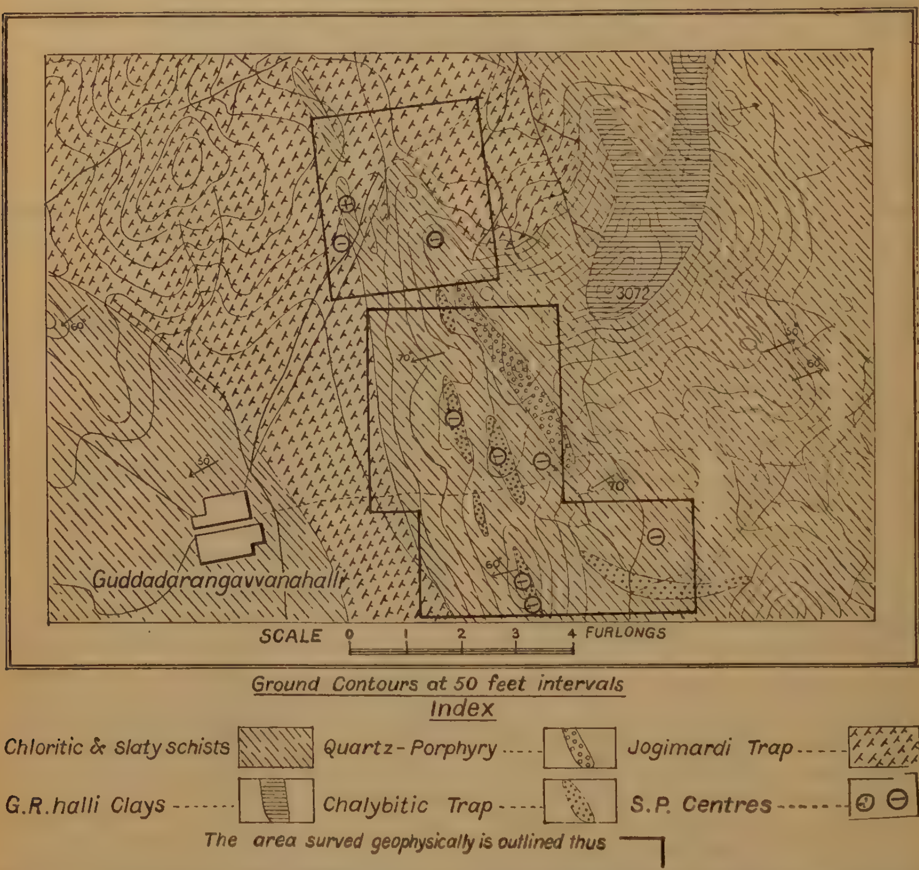

FIG. 1.—GEOLOGICAL MAP OF GUDDADARANGAVVANAHALLI REGION, SHOWING DISTRIBUTION OF SPONTANEOUS POLARIZATION CENTERS.

of the equipotential lines. A direct location of the latter was impracticable because of the unfavorable conditions of the rugged topography and the poor ground contacts. So the potentials were measured along a closely laid out network of stations and the equipotential lines were drawn on a plan, by interpolation. The accuracy of the determinations was established by the satisfactory closure obtained in the various traverses.

The apparatus used consisted of the d.c. potentiometer and a special type of nonpolarizing electrodes. The potentiometer* had four ranges, 0–10, 0–20, 0–50 and 0–100 millivolts, operated by two convenient switches. The instrument was amply sensitive even when dealing with fairly high contact resistances. The nonpolarizing electrodes consisted of half cells with Ag-AgCl electrodes in salt solution. These cells were constructed locally and have

* The potentiometer, designed by Broughton Edge, was supplied by Messrs. H. Tinsley and Co., Ltd., London. This model has some improvements over the original design used by the I.G.E.S. in Australia.

been found to keep well in transport. Their internal polarization is usually within a millivolt. The cells are rather sensitive to external variations of temperature, especially in a tropical climate, and special attention in the field is required in order to obtain a satisfactory performance of the electrodes.

Centers East of the Village

To the east of the village, the spontaneous polarization surveys were carried out along a series of east-west traverse lines laid 200 ft. apart, with stations cut at intervals of 100 ft. along the lines. The traverses were all connected by intermediate points between the lines. The traverse lines were disposed across the strike of the rocks in the area. From the potential measurements made, the equipotential lines were drawn, by interpolation, in plan on a scale of 200 ft. to an inch; this plan, reduced to half that scale, is reproduced here as Fig. 2.

The grounds constituting this block form part of the steep, hilly region (Fig. 1) and, owing to the abundance of outcrops of bare, hard rock and dry surface of the soil, the ground presented a special problem in securing good contacts for the nonpolarizing electrodes. Usually the contacts were prepared by digging deep holes, sometimes more than a foot deep, and abundantly watering the holes a day in advance of the measurements. These holes were again moistened slightly just before the electrodes were placed. This procedure proved generally satisfactory, but one of the disadvantages was that the requisite fresh water had to be brought from long distances.

A glance at Fig. 2 will show that the area bristles with a number of well-defined negative centers. The zones of negative potentials are well bounded by distinct equipotential lines. A detailed mapping of the geological features of this block showed the existence of a considerable agreement between the trends of the equipotential outlines of many of the negative centers, and the outcrops of chalybitic trap occurring as isolated patches and dikes. A few of the negative centers of minor importance were noted in association with other rock types, such as quartz reefs, ferruginous breccia and ochery and calcareous schists. All these rocks possess very high electrical resistivity.

The most characteristic association of the negative centers is clearly at or in the vicinity of the chalybitic trap. This trap, as already mentioned, is an intrusive into the schists, being either a phase of the Jogimardi trap or belonging to the quartz-porphyry series of intrusions. The rock is essentially composed of chlorite, chalybite and calcite with some mica, feldspar and quartz; ilmenite, magnetite and pyrites occur as accessories, the last named mineral being occasionally found in large, well-developed, cubic crystals. Chalybite makes up as much as 50 to 60 per cent of the rock and occurs as distinct rhombohedral crystals. The weathered rock is highly pitted, soft and brownish, owing to the alteration of chalybite into limonitic and ochery material. It is probable that the alteration of chalybite (i.e., the oxidation of the ferrous carbonate into limonite) has played some part in the generation of the spontaneous polarization currents noticed in the area.

In the southeastern corner of the block (Fig. 2) a wide zone of positive potentials with a northwest strike is indicated. An investigation of the ground a little farther southeast of the area shown in the plan was also carried out, to see whether the zone had definite limits. The results, however, showed that the equipotential lines in that portion of the ground began to wander about, without showing a tendency to close up within any limited area. A detailed survey within the area of the positive potentials indicated the existence of a number of weak, local, negative centers but none of any particular significance. The chaly-

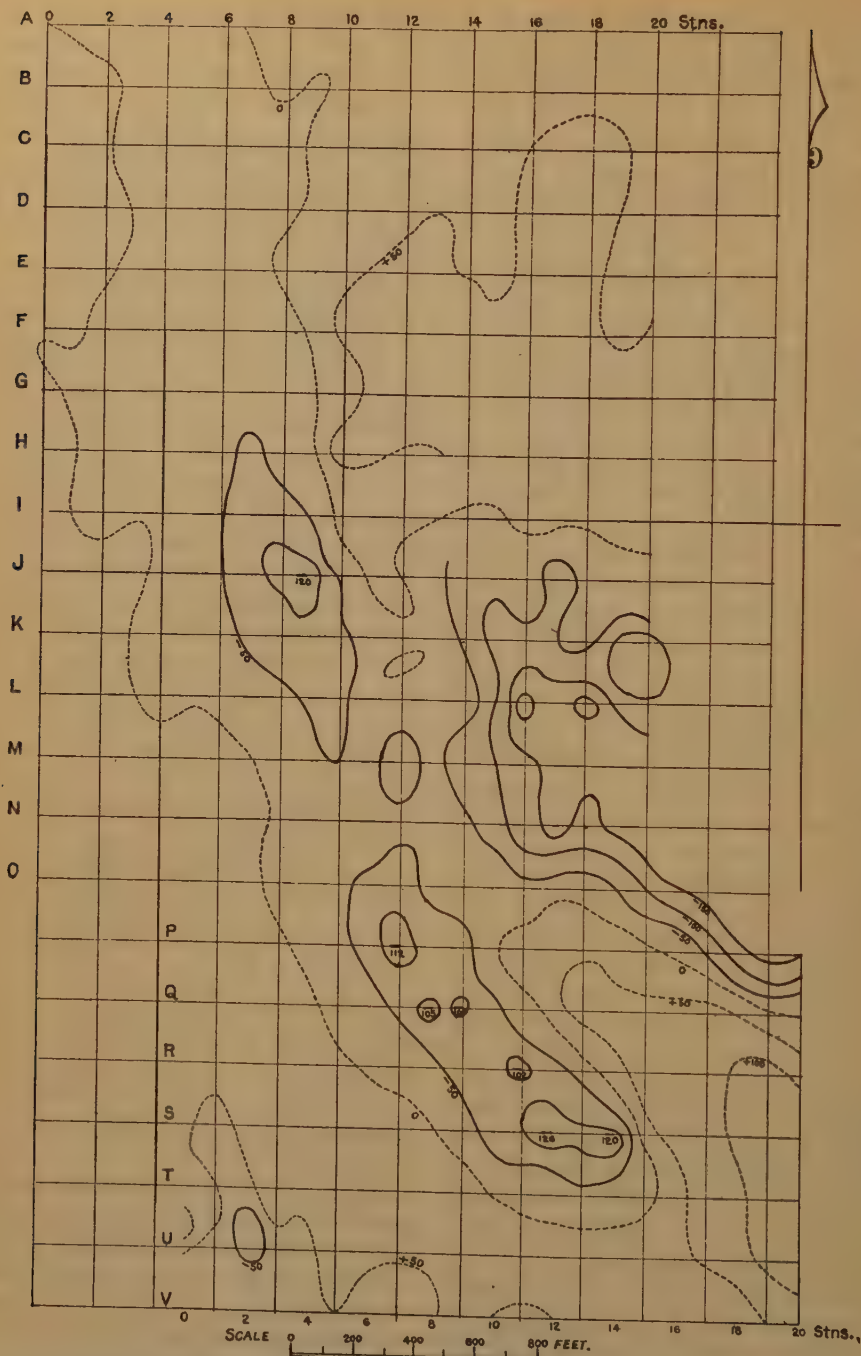

FIG. 2.—SPONTANEOUS POLARIZATION SURVEY, G. R. HALLI EAST AREA, CHITALDRUG DISTRICT. Potential contour intervals are 50 millivolts. Approximate positions of negative centers are marked by a minus sign.

bitic trap in this part of the area carries a noticeably larger amount of pyrites than elsewhere and the soil is strewn with abundant cubes of limonitic pseudomorphs. Two of the prospecting trenches that previously were sunk over this ground have also shown fresh pyrites in the chalybitic trap but the mineral occurs too poorly disseminated to be of any economic value. It seems reasonable to attribute this zone of positive potentials to the disseminated pyrite undergoing oxidation, the absence of any well-defined centers being due apparently to the absence of definite ore bodies.

Centers North of the Village

Some account of the spontaneous polarization surveys carried out in this part of the area has been published,[3] in a detailed report dealing with all the geoelectrical work done in the locality. The account given in this paper is based on revised data obtained since that report was published.

About ¾ mile north northeast of the village, along one of the preliminary traverses,* the spontaneous polarization profile denoted a characteristic trough of negative potentials. A detailed survey in the neighborhood of that line revealed the existence of important positive and negative centers. Fig. 3 shows the distribution of the equipotential lines determined by interpolation. In this plan, although only two prominent centers have been marked out, there are actually several subordinate weak centers lying within the zone of positive potentials. Many of these weak centers are characterized by such small gradients that no clear outlines of the minor equipotential lines could be obtained. The area of positive potentials corresponds very closely with the outcrop of shaly schists that contain gossan material and quartz stringers. A disseminated mineralization appears to exist in the area, with probably a series of small, closely lying, parallel and branching system of lodes. From the inflection of the equipotential curves, it is believed that four important veins are indicated, and their axes have been marked on the plan. Of these, the central one is by far the most prominent, and for this the potential gradient is steepest on the western side, suggesting that the dip of the lode is in that direction.

Since the gossan occurring within the schist looked promising and the finding of an ore body in depth seemed probable, some underground prospecting work was carried out on the central indication. An old prospecting shaft in the vicinity, lying at the contact of the trap with the schists, was deepened to 70 ft. below surface and a crosscut was taken westward from the bottom of this shaft. This crosscut, after passing through the zone of indication, revealed numerous thin ferruginous and quartzose stringers in the schist, all of them highly leached out and without any profitable ore. A winze was sunk on this zone to a depth of 30 ft. and at 25 ft. below the level of the crosscut a well-defined lode of pyritiferous, graphitic schist was encountered. A southerly drive for a length of 12 ft. was taken on the lode, then, owing to the difficulty of pumping out the large quantities of underground water, further prospecting work was discontinued.

This lode is composed of a black, crumpled and sheared clayey schist charged with fine graphite and pyrites. The lode material carries on an average about 20 per cent of pyrite but neither copper nor any other valuable metals have been noted so far.

* This refers to traverse R_2, shown in Fig. 8 and Plate VII of the Record of the Mysore Geol. Dept., vol. 39, pp. 95–96. In the data presented in that report, an error crept in, a consistent mistake having been made in booking the signs of the polarity of the spontaneous polarization readings—positive being noted instead of negative, and vice versa throughout. This error was discovered subsequently and the account given in the present paper is based on the revised and corrected data, obtained during the last field season, February to May 1942.

The carbon content is also very poor. In its attitude the lode conforms very closely with the position marked out on the surface by the geophysical survey. The width of the lode is 2½ ft.; it dips westward at 60°, stroking nearly north-south. The lode occurs at the junction of the intrusive Jogimardi trap with the schists.

According to Slichter,[4] positive peaks are reported to be associated with graphite and the positive center noticed in this area may be attributed to the graphitic character of the lode. Nowhere in the surface outcrops are any graphitic schists seen, and, as a matter of fact, the occurrence of this type of schist has been brought to light only as a result of underground prospecting work carried out for testing the cause of the electrical indication.

Let us now turn our attention once again to the S.P.E.P. plan (Fig. 3) and consider the characters of the prominent negative center near station 12 on G traverse at the southern extremity. In this plan only a part of the equipotential lines around the negative center have been outlined, the southern parts being left out. The potential gradient around this negative center was noted from the profiles to be 0.5 mv. per ft.; in fact, about twice as large as that characterizing the central positive center that occurs on the gossan (the latter had a gradient of only about 0.25 mv. per ft.). In the field, this prominent negative center is seen to

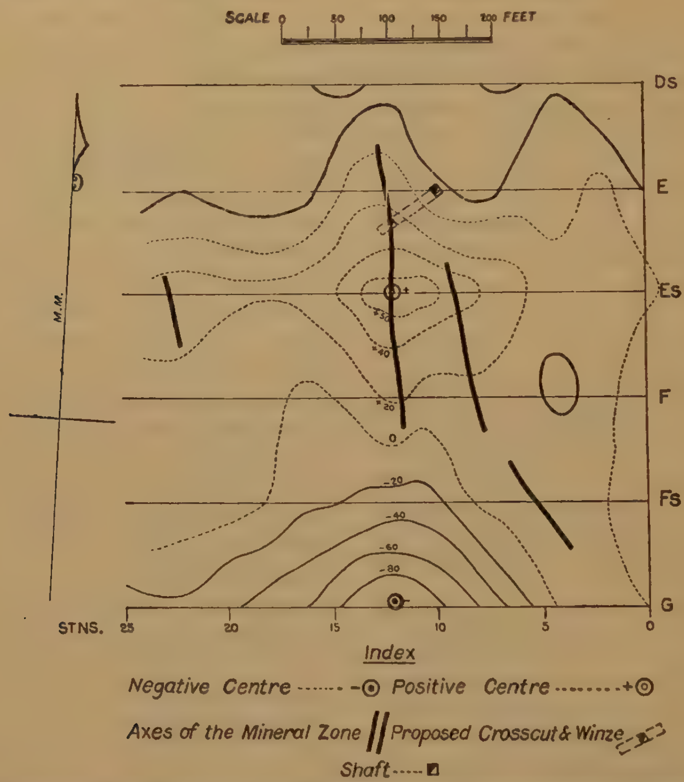

FIG. 3.—SPONTANEOUS POLARIZATION EQUIPOTENTIAL PLAN, GUDDADARANGAVVANAHALLI NORTH AREA.
Potentials expressed in millivolts.

be situated on an outcrop of bouldery trap—a dike of the Jogimardi trap—which is intrusive into the schists. This dike has no visible mineralization; nor does it contain appreciable amounts of any oxidizable and conductive minerals. It is very compact and full of boulders. From the resistivity measurements made here, it was noted that the ground occupied by this dike has a resistivity of the order of 20,000 to 30,000 cm.-ohms, while the adjoining schists have resistivities varying from 4000 to 6000 cm.-ohms. The negative center occurs within an area of high resistance and appears to have no direct relation to the existence of an ore body. It is probable that the spontaneous polarization center is connected with some secondary effects, perhaps those of subterranean water running along the contact of the dike with the schists.

Spontaneous Polarization Centers in Relation to the Topography

One other feature noticed in the surveys near Guddadarangavvanahalli may also appropriately be mentioned here. An apparent relation between the topographic features and the distribution of the spontaneous polarization centers appears to exist in the area. The zones of negative potentials outlined in Fig. 1 are confined to the hilly ground, very often conforming to the crests of the ridges, while the positive potentials are distributed over the lower grounds and valleys; that is to say, the natural earth currents flow into the hills from the surrounding valleys and plain. Ambronn[5] cites numerous instances of the current in the mountain ranges almost always flowing uphill, from valley to mountain. In the area under report, also, some of the hills are negative in relation to the lower grounds, and this feature is in large measure due, circumstantially, to the potentials associated with the chalybitic trap, which occurs mostly along the crests of the ridges. Since the masses of this chalybitic trap are pyritic to some extent, and have finite shape and size with clearly bounded surfaces, the equipotential outlines around them exhibit distinct closure, with one or more definite centers. Thus, the agreement in the dispositions of the negative potentials with the hills is more or less of an incidental character.

Conclusion

From the foregoing account, it is clear that the self-potential centers noted in this area are due to various causes and that the negative centers noticeable do not indicate the occurrence of any important ore bodies. To the north of Guddadarangavvanahalli, the positive center has been found to correspond exactly in position with a definite lode of pyritiferous graphitic schist, the apex of this lode having been discovered at a depth of about 100 ft. below surface, as a result of the underground prospecting that was especially undertaken to test the cause of indication.

From the results of the surveys carried out near Guddadarangavvanahalli, it may be stated that a very close study of the geological conditions is essential for properly interpreting the electrical indications.

References

1. P. Sampat Iyengar: Report on the Survey Work in the Chitaldrug District. *Records*, Mysore Geol. Dept. (1906) **6**, 72–90.
   B. Rama Rao: Mineral Survey of the Sulphide Zone near Chitaldrug. *Bull.*, Mysore Geol. Dept. (1932) No. 12, 1–14
2. A. Broughton Edge and T. H. Laby: The Principle and Practice of Geophysical Prospecting. Rept. of the Imperial Geophysical Experimental Survey (1931) 15–19.
3. M. B. Ramachandra Rao: Report on the Geophysical Survey near Guddadarangavvanahalli in Chitaldrug District. *Records*, Mysore Geol. Dept. (1941) **39**, 94–98.
4. L. B. Slichter: Discussion. *Trans.* A.I.M.E. (1932) **97**, 35.
5. R. Ambronn: Elements of Geophysics, 1928 149–150.

DISCUSSION

S. F. Kelly.*—This able study by M. B. Ramachandra Rao presents several points

* Sherwin F. Kelly Geophysical Services Inc., Wilmington, Del.; Geophysical Explorations Ltd., Toronto, Ont., Canada.

of interest deserving of further discussion—the negative centers in the chalybitic traps, the adjacent area of positive potentials, the positive center on a graphite-pyrite lode, and the near-by negative center on a dike of the Jogimardi trap.

Before entering into this discussion, however, I have two comments to make on the field procedure. The author states that he laid out his traverse lines at 200-ft. intervals, and occupied stations along these lines at 100-ft. intervals. From my own experience, I believe that this is too wide a spacing of the observation stations to permit good interpretation. For close reconnaissance I prefer traverse lines at 100-ft. intervals, with observation stations 50 ft. apart, and for detail work often employ stations at 10-ft. intervals on traverse lines 25 ft. apart. This permits an accurate delineation of the equipotential lines, the exact determination of the maximum ground potentials, and the differentiation of the negative (or positive) centers, if several exist.

The watering of ground contacts is occasionally necessary in very dry earth, but probably not as often as is sometimes thought; a nonpolarizing electrode with good porosity will usually permit sufficient copper sulphate solution to seep through to produce an adequate reduction of the contact resistance. Where moistening of the ground is necessary, it can introduce serious errors in the readings, unless due cognizance is taken of the fact that electrocapillary potentials will occur while the moisture is moving into the pore spaces of the ground.

The author notes the characteristic association of negative centers with the chalybitic trap, and postulates that the oxidation of the ferrous carbonate into limonite plays some part in the generation of the observed spontaneous polarization currents. I am inclined to doubt this explanation, as the generation of spontaneous polarization currents depends upon the electrochemical interaction between metallic conductors and surrounding electrolytes; the carbonate is not a metallic conductor, and is therefore incapable of playing any part in such a reaction. The explanation, I am sure, is to be found in the pyrite present in the trap. The author comments on the occurrence of this mineral, and notes that cubes of limonitic pseudomorphs are in places abundant. It is highly probable that weak, local concentrations of pyrite in the trap, possibly as insignificant veinlets, are responsible for the negative centers observed.

These negative centers show two characteristics consonant with this explanation. In the first place, the potentials are weak, apparently ranging between minus 100 and minus 150 millivolts. In the second place, the width of the reactions, measured at the minus 50-mv. level, is narrow, usually less than 200 ft. From these facts, two conclusions can be drawn; the weak voltages imply a disseminated mineralization, not massive sulphides; the very narrow width of the zone of electrical potentials indicates short extension in depth of the causative sulphide concentration. By contrast, a body of massive sulphides whose apex is close to the surface will usually produce a potential of minus 300 mv. or more, and if it has good extension in depth, the electrical activity it causes will be observed for several hundred feet on both sides of the vein.

On these grounds, the negative centers shown in Fig. 2 look as though they were caused by discontinuous, small pods of weak sulphide mineralization along fractures in the trap. Is it not possible that the traps have been fractured and invaded by hydrothermal solutions, which produced the iron carbonate and deposited some sulphides in fracture zones?

The indicated shallowness of the weak sulphide mineralization, furthermore, is linked to the neighboring positive potentials. This is particularly true in the southeast corner of Fig. 2, where an area of moderate positive potentials is pinched between two zones of negative potentials. This positive area is caused, I believe, by the upflowing currents emerging from the lower poles of those same sulphide pods responsible for the negative centers. This upflowing current is necessary to complete the circuit, of course, and is more noticeable when the pole from which it emerges is close to the surface. If the pole is deeply buried, the currents will be more widely spread, and the positive areas less noticeable than when the pole is at shallow depth and the currents travel to the surface pole in a shorter circuit. Under these circumstances, two closely spaced negative zones will naturally produce an intensified positive one lying

between them; this is exemplified in the author's Fig. 2.

The most interesting phenomenon recorded in this paper is the center of positive potentials beneath which a pyrite-graphite lode was discovered. This, I believe, is due to a set of circumstances not usually encountered, but is readily explained when the electrochemical processes involved are fully understood. R. C. Wells[6] of the U.S.G.S., and the late Prof. Conrad Schlumberger[7] of the Paris Ecole des Mines, have published the results of their independent pioneer investigations on the possible chemical processes involved in the spontaneous generation of electrical currents by sulphide bodies. My own laboratory experiments and field investigations, however, lead me to ascribe the principal, but not the sole role in this electrochemical phenomenon, to the difference in acidity between the waters bathing the apical portions of the sulphide deposit, and those waters in contact with the lower reaches of the mineral body. For example, at the apex of a small sulphide lens, I have found the water percolating through the ore body to have a pH* of 3 or less; i.e., this water was strongly acid. At the bottom of the lens, some 300 or 400 ft. deeper, the water issuing from the lower end of the sulphide body gave a pH of 8, or slightly alkaline. Laboratory tests show that the single-electrode potential of a piece of sulphide against acid solutions is markedly different from its potential against alkaline solutions. As a result of such differences, an electric current will flow from the region of the acid medium, through the metallic conductor to the zone of the alkaline electrolyte; the circuit in the enclosing wall rocks is then from the alkaline electrolyte at depth to the acid one at the surface, and back into the apex of the metallicly conductive body. This directional flow must be kept in mind in order to understand the anomalous potentials recorded by M. B. Ramachandra Rao.

The acid waters near the apex of a sulphide body doubtless result from the interaction between normal surface waters and the sulphide minerals; the maximum acidity is then encountered in the immediate vicinity of the sulphide apex. As oxidation progressively moves the sulphide apex deeper into the ground, this zone of maximum acidity will also migrate downward. In the deposit under consideration, oxidation apparently had removed all trace of the sulphides to a depth of 100 ft. It is therefore at this depth that the maximum acidity of the ground waters is to be expected, and at this depth the current circulating in the surrounding rocks will flow back into the sulphide vein. Under normal circumstances, this results merely in observing, at the surface of the ground, a negative potential that is slightly weaker than it would be were the sulphide apex still at the grass roots. The case here cited is not normal, however, because graphite is present in the body, and has not been removed by the processes of weathering and oxidation. It therefore persists *above* the sulphides, and presents a zone of metallic conductivity extending upward through the leached gossan.

Since the maximum acidity of the ground waters is found at the sulphide apex, at a depth of 100 ft., the surface waters in contact with the upper end of the graphitic material are less acid, and the consequent flow of current is from the acid zone upward through the graphitic deposit to the surface, where it flows *outward* from the graphitic apex. *This produces a zone of positive potentials at that point.* The current flows downward through the country rock to the acid zone, where it flows in to the lode. At the same time there is probably another circulation of current downward from the sulphide apex, through the pyrite-graphite mineralization to a zone of less acid (or alkaline) waters at depth, where it flows outward and upward in the country rock, returning to the acid zone and the top of the sulphide vein.

This flow of current may readily be pictured in cross section through the vein as forming a figure 8. If arrows represent the direction of current flow, they will form the figure 8, with

[6] R. C. Wells: Electrical Activity in Ore Deposits. U. S. Geol. Survey *Bull.* 548 (1914).

[7] C. Schlumberger: Etude sur la prospection sous sol. Paris, 1920 Gauthier-Villars. Translated into English by S. F. Kelly, under direction of the author. An abstract of the translation (Study of Underground Prospecting) appeared in *Eng. and Min. Jnl.* (May 7 and 14, 1921) 111, 782–788, 818–823.

* The term pH is used as a measure of the acidity or alkalinity of a solution. The pH figure is the logarithm of the number of liters containing one active gram-ion of H^-. A pH 0 is therefore a strong acid solution, and pH 15 is a strong alkaline one. A neutral solution has a pH 7.5.

their points directed inward at the waist of the 8, their target being the apex of the sulphide zone in its milieu of acid electrolyte, the negative pole. The tails of the arrows emerge from the positive poles, one at the surface. the other at depth.

In confirmation of this explanation the author recently communicated to me the fact that the sulphides have been completely leached out to a depth of about 100 ft. and that the water struck in the winze that was put down to test the indication was quite fresh. Graphitic material, devoid of pyrite, was found at the level of the water table.

From what has been said in the foregoing paragraphs it is evident that, under normal circumstances, a graphitic deposit lacking important sulphide mineralization would show a negative center at the surface of the ground. This is in contradiction to some published statements that graphite shows positive centers. I am convinced that such positive centers are due solely to abnormal conditions such as those described in the paper under discussion. From my own field experience, and from published papers by others, there is abundant evidence to show that normally the potential observable over a deposit of graphite, in schists or pegmatites, is a negative one. In fact, M. B. Ramachandra Rao recently informed me that a spontaneous polarization survey had resulted in the discovery of a workable body of graphite under a negative center in the Kolar schist belt. The indicating potential was about minus 300 millivolts.

The negative center observed on the extension of the strike of the pyrite-graphite lode shown in Fig. 3 is susceptible of two explanations. It represents either an extension of the same lode, in which more normal electrochemical conditions exist, or it may represent a more highly conductive zone than the immediate surroundings, due to fractures or mineralization at the schist-trap contact, along which the current outflowing at the surface from the graphitic lode is being concentrated in its downward flow to complete the circuit. In any event the weak potentials and narrow width of the zone certainly indicate that any sulphides present would be weakly disseminated and of unimportant size. In a personal communication to me the author has commented on the inadequacy of the phenomenon of "steaming potentials" (potentiais due to flow of water) to explain this anomaly, and postulates that the accessory "ore minerals" of the dike may form a conductor adequate to establish the current circuit.

The author, M. B. Ramachandra Rao, is to be congratulated on his careful geophysical work in this prospecting campaign, and to be thanked for making it available for publication. Case histories of this type are needed to furnish a broad and sound basis for understanding and evaluating geophysical methods. This is especially true with respect to the spontaneous polarization method, which is sometimes overlooked in spite of the fact that it remains the most reliable and efficient geophysical technique for detecting sulphide concentrations.

Use of the Geiger-Müller Counter in the Search for Pitchblende-bearing Veins at Great Bear Lake, Canada

By G. Carman Ridland,* Junior Member A.I.M.E.

(New York Meeting, February 1943)

Abstract

In conjunction with a geological investigation of the silver-bearing veins at Contact Lake, Northwest Territories, Canada, a survey was made with a Geiger-Müller counter of the gamma-ray emissions from the rocks in the vicinity of the mine workings.

Discontinuous pitchblende veins have been encountered occasionally in the silver-bearing fissures, and the geophysical survey was undertaken with the hope that abnormally high gamma-ray intensities, if detected, might lead to larger and more continuous pitchblende discoveries.

Before the instrument was used at Contact Lake, preliminary tests were made, first with laboratory specimens at Princeton University, and later over known pitchblende deposits at the Eldorado property, LaBine Point, N.W.T.

The Geiger-Müller counter, as adapted for field use, is described; the technique of transporting and operating the instrument is outlined; and the general precautions to be observed are discussed.

The results obtained at Great Bear Lake show that the instrument is capable of detecting not only a pitchblende ore shoot in a shear zone, but also the mildly radioactive "host rock" at a considerable distance from the ore body. Hence, use of the Geiger-Müller counter is urged, not just for the detailed search for an ore body in a shear zone, but for the detection of possible radioactive "host rocks" in large-scale reconnaissance surveys of unexplored regions made by prospectors and members of federal geological survey parties.

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Introduction

Location.—Along the rocky eastern shores of Great Bear Lake, in the Northwest Territories of Canada, lies one of the world's great radium-producing areas. The Eldorado mine, owned and operated by the Eldorado Gold Mines, Ltd., is at LaBine Point; while the Contact Lake mine, operated by Bear Exploration and Radium, Ltd. (B.E.A.R.), lies 9 miles to the southeast of LaBine Point and 2 miles south of Echo Bay, an indentation in the eastern shore line of Great Bear Lake.

Geology.—The Eldorado company obtains its radium by the mining of the mineral pitchblende, which is found associated with a complex variety of metallic and nonmetallic minerals[1] in quartz-carbonate veins occurring in metamorphosed pre-Cambrian sedimentaries. Most of the pitchblende is intimately associated with a brown quartz and belongs to an early hydrothermal stage of mineralization during which safflorite-rammelsbergite and minor cobalt-nickel minerals were also deposited. Some pitchblende occurs with a group of minerals belonging to a later stage of mineralization in which the gangue is mainly dolomite and sometimes ferruginous rhodochrosite. Associated with this group are native silver and lead-zinc-copper sulphide minerals. The Contact Lake property owes its existence to the mining of rich, native silver ore shoots, which are

[1] D. F. Kidd and M. H. Haycock: Mineragraphy of the Ores of Great Bear Lake. *Bull.* Geol. Soc. Amer. (1935) 46, 879–960.

found with a mineral assemblage almost identical to that of the LaBine Point deposits, in fissure veins cutting a dark brown, medium-grained, homogeneous,

FIG. 1.—THE GEIGER-MÜLLER COUNTER AND BOX IN WHICH IT IS SHIPPED. (*Photo courtesy of C. L. Hershman.*)

pre-Cambrian granodiorite. Occasionally, well-defined lenses of pitchblende have been encountered with the silver, and a small, annual production of pitchblende has resulted.

Purpose.—In the summer of 1939 the writer was instructed to make a detailed geological survey of the surface and underground workings at Contact Lake for the purpose of guiding exploration in a direction where larger concentrations of pitchblende were likely to exist. The geological study was supplemented by a geophysical survey of the gamma-ray emanations from the rocks in the vicinity of the mine workings. Where pitchblende occurs, the rocks are radioactive, and if areas could be detected where gamma-ray intensities were above normal, they might lead to further discoveries of radioactive ore.

CONSTRUCTION AND OPERATION OF THE APPARATUS

Construction.—The Geiger-Müller counter is an apparatus for detecting and measuring gamma-ray emissions. The portable instrument used at Great Bear Lake was designed by Dr. G. L. Locher, of the Bartol Research Foundation, Swarthmore, Pennsylvania, and built by Herbach and Rademan, Inc., Philadelphia, to meet specifications adapting it for use in the field. The apparatus is composed of three parts: a counter section, a power section, and a set of telephone receivers (Fig. 1).

The Counter Section is enclosed in an 11 by 7 by 3 in. metal case. The sides of the case, except one, which is aluminum, are steel. The counter section contains two counter tubes of different sizes, a switch that permits operation of either the large or the small tube, but not both at the same time, an amplifying system that transmits the counter discharges to the earphones, and two jacks to accommodate two sets of earphones, so that two observers may listen in at the same time. The large, or sensitive tube, identified by Herbach and Rademan as type GLC-11, is the one most commonly used. The small tube, type GLC-10, is switched in to replace the sensitive tube only when the radiation is so intense that discharges from the large tube occur too rapidly to be counted accurately.

The Counter Tube.—The essential parts of a counter tube are:[2] a 0.003-in. bare tungsten wire (*A*, Fig. 2); a hollow, thin-walled, metal cylinder *B*; and a suitable mixture of hydrogen and neon gas sealed in a Pyrex tube *C*. The wire is stretched from one end of the tube to the other through the axis of the cylinder, as illustrated in Fig. 2. Just a sufficient difference in potential is created between the cylinder

[2] A more complete description of a Geiger-Müller counter may be found in a paper by G. L. Locher: The Use of Geiger-Müller Counters for Locating Radium and for Measuring Gamma-Ray Intensities. *Radiology* (Aug. 1936) 27 (2), 149–157.

electrode (cathode) and the wire electrode (anode) to almost cause a brush discharge between the electrodes. In this sensitive state any ray entering the tube (at *D*), and possessing the ability to ionize the gas sufficiently to conduct the current across the gap between the electrodes, will produce a discharge that will be registered by the amplification system (at *E*). Immediately after the discharge, the potential is again built up, and the tube is ready to "count" the next ray that enters the tube. The discharges are heard as sharp clicks by means of earphones. The frequency of the clicks is a measure of the intensity of the radiation, and hence, is quantitative.

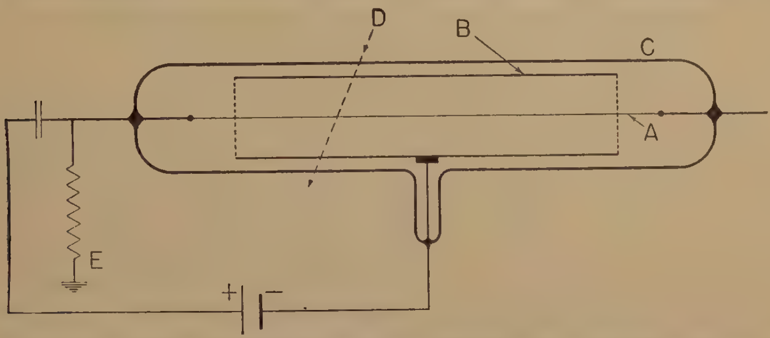

FIG. 2.—DIAGRAM SHOWING FUNDAMENTALS OF A GEIGER-MÜLLER COUNTER TUBE. (*After G. L. Locher.*)

The Power Section is enclosed in a rugged, 11¼ by 12¼ by 8⅛-in. steel case, and consists of:

12 high-voltage batteries, No. Z30N (45 V.)
4 C-batteries, No. 4156
2 dry cells, No. 4FH

The high-voltage batteries are connected in series to supply a potential ranging from 485 to 530 volts for the counter tubes. The C-batteries and dry cells furnish the filament and plate voltages, respectively, for the one-stage amplifier tube. The power case and the counter case are attached to each other to form a single unit (Fig. 1) weighing exactly 40 pounds.

The Background Count.—Unfortunately, a counter suitable for detecting gamma rays is also sensitive to cosmic rays. It is impossible in the field to shield cosmic rays from the tube; they are continually causing a highly irregular, "background" counting rate for which allowance must be made when gamma rays are to be measured. In order to estimate this cosmic effect, it is necessary to put the instrument down on the ground and count the discharges over a definite period of time, then compare the average to other averages determined at previous positions, or "count stations." If they check within certain limits, and the operator has no reason to suspect any gamma-ray influence, it is concluded that the average count at a certain position is just the normal, spontaneous rate. Theorectically, a count should be taken for a period of several hours to obtain an average that can be duplicated exactly at any time.* However, for practical purposes

* With regard to my work with the counter, I frequently obtained differences of over 50 per cent from normal. For instance, counting over granodiorite that regularly was running between 80 and 90 per minute, I sometimes recorded 40 for a one-minute count and the following one-minute count might be 52, or it might be 120. That is why I found it necessary to average 10 or 12 one-minute counts to obtain a figure approximating the normal.

Occasionally this 10-count average would not look right. If it was low, it was ignored; if it appeared high for no apparent reason geologically, it might be repeated. I frequently checked stations the following day where I had obtained higher-than-average counts and found the counts to be back near normal again. If high counts persisted, and particularly if they occurred in the proximity of a possible ore zone as they usually did, they were then considered anomalies.

in the field, a count taken over a period of 12 min., or possibly 10 min., produces an average (per minute) that is reasonably close to the exact figure.* lashed to a packboard in such a position that the counter case and its aluminum side are toward the ground (Fig. 3). It is carried on the back of the operator by means of the

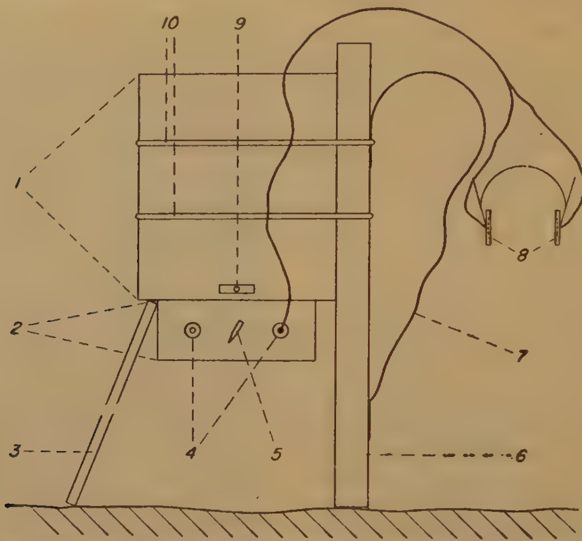

FIG. 3.—DIAGRAMMATIC SKETCH SHOWING INSTRUMENT LASHED TO PACKBOARD AND PROPPED ON GROUND IN POSITION FOR A COUNT.

1. power section; 2, counter section (the side facing the ground is of aluminum); 3, wooden stick used for temporary support of the instrument; 4, jacks for the telephone receivers; 5, counter switch; 6, leg of packboard; 7, shoulder strap of packboard; 8, telephone receivers; 9, battery switch; 10, rope holding instrument to packboard.

Technique of Transporting and Operating the Instrument.—The apparatus, when in transit and not in use, is carried in a strong, well-padded, wooden box (Fig. 1). Spare parts and equipment required to make emergency repairs are carried in a second, less rugged box. The complete outfit weighs 100 lb. When in use in the field, only the 40-lb. unit is transported. It is securely shoulder straps of the packboard. The operator wears the earphones and listens to the reports as he walks from one Geiger-count station to another. In addition to the instrument, he carries a bag containing a stop watch, a small axe, a marking pencil, a notebook and pencil, and a small wooden stick used to support the instrument when it is placed on the ground (Fig. 3). At Contact Lake the day's traverse was planned in advance with reference to the geology and topography. Count stations were taken along the traverse at intervals of from 50 to 150 ft.; or were chosen at any place where there appeared to be a rapid change in the discharge rate, or at any place where, from geological evidence such as a fault zone, shear zone, or mineralized zone, there was suspicion of gamma-ray emanation. When a station was reached,

* Credit is given here to Dr. Locher, who painstakingly designed the large tube for this instrument to detect most efficiently a weak gamma-ray radiation from a pitchblende source. The reader may appreciate the fact that a tube, designed for the purpose of locating a highly radioactive source, such as a misplaced radium needle in a hospital, would not necessarily have sufficient sensitivity to detect the weaker emissions of a deeply buried uranium compound. On the other hand, a tube can easily be made too sensitive. In this case the tube would be so susceptible to cosmic influence that a weak gamma-ray source could not be recognized through the heavy, cosmic background.

the instrument was propped on the ground and the count taken. As the count was recorded, an identification number was assigned to the station. Then a stake was shielding effect of the building, and inside the building the spontaneous clicking was reduced to a rate varying between 10 and 20 per minute.

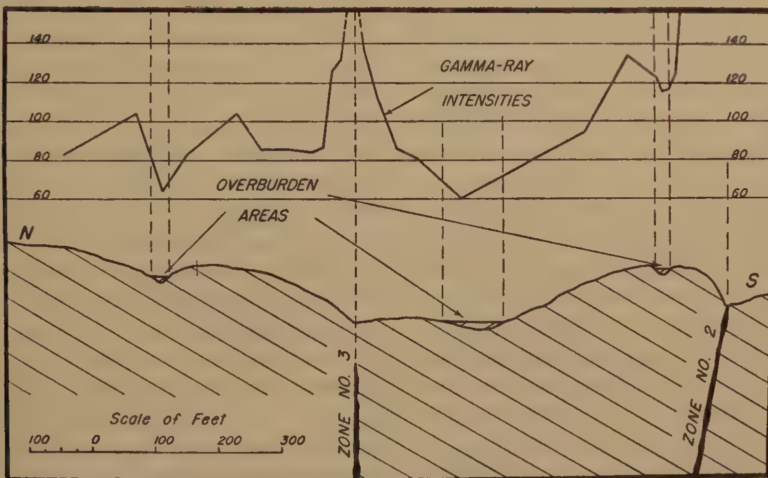

FIG. 4.—PROFILE OF GAMMA-RAY INTENSITIES RECORDED OVER THE NO. 2 AND NO. 3 ZONES AND OVERBURDEN AREAS AT LABINE POINT.

The area shaded with parallel lines running downward to the right represents bedrock. The two heavy lines represent pitchblende ore bodies in shear zones. The points in the gamma-ray intensity curve, where changes in direction take place, represent positions where Geiger counts were taken.

cut, marked with the number, and driven into the ground beside the instrument. Later, the Geiger-count stations were relocated by plane-table traverse and tied into a transit base loop.

PRELIMINARY TESTS

Before the Geiger-Müller counter was taken to the Contact Lake property, it was tested in the geological laboratories and on the playing fields of Princeton University, and over actual radioactive deposits at LaBine Point.

Tests at Princeton, New Jersey.—The following observations were noted from the tests at Princeton:

1. On an open playing field the background count was found to be between 50 and 52 per minute.

2. As the instrument was carried toward a five-story building, the background count rapidly fell off, apparently because of the shielding effect of the building, and inside the building the spontaneous clicking was reduced to a rate varying between 10 and 20 per minute.

3. The apparatus was noticeably more sensitive to radiation from pitchblende specimens inside the building than outside.

4. On an open field, 50 lb. of Great Bear Lake specimens, rich in pitchblende, were detected at a distance of 20 ft. above the background count by averaging 12 one-minute counts.

5. Gamma rays from the 50 lb. of radioactive material were detected through more than 5½ ft. of soft, earthy overburden. This, or course, did not indicate through what thickness of rock covering an ore body of pitchblende could be detected, but tests at LaBine Point helped to answer this question.

Tests at LaBine Point, Northwest Territories.—The results of a traverse across the No. 2 and No. 3 zones at the Eldorado property can best be illustrated by the accompanying profile sketch (Fig. 4). These zones were ideally suited for the tests, for

the ore body in No. 2 zone is exposed at the surface and the ore body in No. 3 zone comes only within 60 ft. of the surface. The following observations were noted:

1. A background count of 80 to 90 per minute on barren country rock was considerably higher than the background count of 60 to 65 per minute on overburden areas.

2. The background count of 60 to 65 for overburden at LaBine Point was not consistent with the 50 to 52 count for overburden at Princeton. This may be due to the difference in cosmic effect at the two localities because of widely varying latitudes.*

3. The activity was so intense over No. 2 zone, where the ore was exposed at the surface, that neither the sensitive nor the small tube could be switched on without possible damage to the instrument.

4. The emanations were readily detected by the Geiger-Müller counter over No. 3 zone, where the ore is within 60 ft. of the surface.

Geiger-Müller Survey at Contact Lake

Procedure.—Attention was necessarily confined to a section one square mile in area—a small part of the extensive B.E.A.R. holdings at Contact Lake. This area included the mine workings and known surface discoveries. Detailed topographic and geologic mapping preceded the geophysical survey. Ten major shear zones of possible economic importance were mapped.

The Geiger-Müller survey was begun with two objectives in mind:

1. To dot the map area as homogeneously as possible with Geiger-count stations.

2. To explore the shear zones with transverse and longitudinal traverses.

The purpose of the first objective was to establish background counts for the various rock types and overburden areas. The second objective was, obviously, to test possible ore structures for evidence of radioactivity.

Results over the Formations.—Three main geological formations were recognized: a light gray, coarse-grained granite; a dark brown, medium-grained granodiorite; and a fine-grained porphyry. The counts taken over the granite and granodiorite approximated those recorded over the sedimentaries at LaBine Point; namely, ranging between 80 and 90 per minute. Over porphyry, a background count of 60 was established. (As a result of these widely divergent background counts, the contact between the diorite and porphyry might easily be traced with a Geiger-Müller counter.) Counts of 60 to 65 were obtained on overburden, which covered either the diorite or the porphyry.

Results over the Shear Zones were far from disappointing. Nine of the 10 zones of possible economic interest were traversed with the counter. Four gave negative results, two produced definite anomalies, and three reacted favorably enough to warrant the recommendation of definite exploration programs.

General Precautions

Several precautions should be observed when the Geiger-Müller counter is used in the search for radioactive deposits.

1. The background count for a particular counter tube is characteristic of that tube only. If it is ever necessary to change a tube in the course of a survey, the background count should be reestablished.

2. The background count in one locality may not necessarily be the same at a new locality even if the same tube is used in both places. Differences in latitude, elevation, or magnetic behavior of a region may be responsible for influencing the count.

3. An electric storm may discharge a counter tube, or may produce false reports in the amplification system; hence, when a

* The approximate latitude of LaBine Point is 66° 05′ N. while that of Princeton is 40° 21′ N.

thunder storm appears on the horizon, it is advisable to postpone the survey.

4. Extra precaution should be taken to keep the instrument dry at all times. A 500-volt circuit, when shorted, will cause serious damage.

5. The background count may be thrown off by the shielding of cosmic rays. A high building, a thick forest, or a steep cliff might be responsible.

6. Radioactive dust must be avoided. A small amount of dust scattered around the inside of the counter case will throw off the established background constant, or will seriously impair the sensitivity of the counter for detecting gamma rays.

a. The instrument should not be taken near a plant where radioactive minerals are being crushed and treated.

b. The apparatus should not be used extensively underground where radioactive minerals are being mined.

c. An operator should keep his clothing, particularly his boots, free from any stray radioactive dust.

Conclusions

The results obtained with the Geiger-Müller counter at Great Bear Lake demonstrate that the instrument can be of value in the search for radioactive ore. There is no doubt that the instrument detected the presence of pitchblende at the surface, and it certainly registered an anomaly over an ore body that is 60 ft. away from the surface.

The future may hold a variety of other practical uses for the Geiger-Müller counter in addition to the one just outlined and the many present-day laboratory uses. For instance, it might be used with certain adaptations to sort radioactive material on a picking table in a mill. It could be used to replace the electroscope in an assay office of a radium mine. It might be used to define a geologic contact between radioactive and nonactive formations. Another practical use—the detection of high grading—was demonstrated to the writer at LaBine Point when the manager, Mr. E. J. Walli, carried a counter into a bunkhouse and found a considerable quantity of high-quality pitchblende specimens in the personal belongings of employees.

The writer believes that the Geiger-Müller counter is not only adaptable to the detailed search for radioactive ore bodies in established radioactive territories, but could, and should, be used by prospectors and members of federal geological survey parties in their aerial reconnaissances of large, unexplored regions. It is recalled that the sedimentary rocks at LaBine Point and the granodiorite at Contact Lake registered decidedly higher counts than the surrounding overburden areas. This indicates widespread distribution of gamma-ray activity in the vicinity of commercial radioactive deposits. Counts taken at widely scattered points over granite batholiths, or extensive sedimentaries, or large basic intrusives in unexplored regions would accurately and rapidly detect any such existing phenomenon which, in turn, would lead to detailed prospecting for radioactive mineral deposits.

Acknowledgments

Professor Edward Sampson, of Princeton University, suggested the use of the Geiger-Müller counter and advised B.E.A.R. on the general plan for field studies. Mr. C. L. Hershman, General Manager of B.E.A.R., enthusiastically supported the work. Mr. Gilbert LaBine, President of Eldorado Gold Mines, Ltd., greatly assisted the work by permitting preliminary tests to be made over the Eldorado ore bodies at LaBine Point. Mr. E. J. Walli, Resident Manager at the Eldorado mine, generously contributed his time and hospitality during the writer's visit at that property. The facilities of the Johns-Manville Research Laboratories were made use of in the preparation of the manuscript. To all of these, the writer is deeply grateful.

DISCUSSION

H. S. Spence.*—The author's survey of ground at Great Bear Lake with the aid of the Geiger-Müller counter is of interest for the results he obtained. It will be even more interesting if further development work on the Contact Lake property, based on these results, proves to support their reliability as a useful indicator of the presence of radium-bearing mineral in situ. Work on the property was suspended in 1939, but it was taken over in 1942 by a new company, International Uranium Mining Co., which has announced plans for reopening it.

With respect to the author's comment on the results obtained on the No. 3 Eldorado vein or zone, at La Bine Point, I fancy he is in error in stating that the ore there comes only to within 60 ft. of the surface. My examination of the Eldorado property[1] showed the No. 3 vein as a surface outcrop, not as wide or well defined, it is true, as those on the No. 1 and No. 2 veins; but the small, reticulating pitchblende veinlets there were remarkable for the intensity of the autoradiographic image they yielded, which was considerably stronger than that produced by the ore of the No. 1 and No. 2 veins. The reason for this was not determined. It would seem very doubtful whether ore lying beneath 60 ft. of bedrock would affect the instrument to any extent.

As bearing on errors likely to be introduced by variations in the "background count" due to fluctuations in cosmic ray intensity, it may be noted that an article in *Nature*[2] for March 13, 1943 showed that intensity variations up to 30 per cent of normal have been registered, and the possibility of misleading results due to such fluctuations would need to be carefully guarded against.

Two references,[3,4] in addition to those cited by the author, are of interest in connection with his paper:

G. C. Ridland (author's reply).—The No. 3 Eldorado vein is exposed for several hundred feet and although pitchblende does occur in some places on the surface, it does not occur continuously over the full, exposed length. The transverse traverse across the No. 3 lode depicted by the writer was made at one of the many points on the No. 3 where pitchblende does not occur. Information supplied the writer by Eldorado mine officials was that in the drift below this particular point (marked by the collar of a ventilation raise) on the vein, and for several feet on either side of this point, pitchblende ore was encountered. Stoping of ore progressed favorably upward to within 60 ft. of the surface, where pitchblende completely disappeared. The 60-ft. raise that was pushed through to the surface for ventilation purposes did not encounter any pitchblende. Hence, it fairly reasonably can be assumed that the pitchblende in the vein nearest the point that the traverse crossed the vein was 60 ft. below the surface.

The writer does not wish to imply that the ore 60 ft. below the surface caused the anomaly, for all the pitchblende, or most of it, had been removed before the traverse was made. Two explanations are possible: first, the presence of the pitchblende lying next to the country rock from pre-Cambrian time to the present has induced a radioactive halo around it in the country rock, and when the pitchblende has been removed the enclosing rock retains its activity; second, the mineralizing solutions that rose in the fissure possibly contaminated the barren vein material and its adjacent wall rock with minute traces of radioactive compounds some distance from where the pitchblende was concentrated.

With regard to Mr. Spence's comment on "background count," a geologic formation or structure that does not increase the count by at least 50 per cent would be considered so mildly radioactive as to be of little or no interest. Hence, a 30 per cent fluctuation from normal for cosmic ray intensities should not have any misleading effect.

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* Department of Mines and Resources, Mines and Geology Branch, Ottawa, Ont., Canada.

[1] H. S. Spence: The Pitchblende and Silver Discoveries at Great Bear Lake, Northwest Territories. Investigations in Mineral Resources and the Mining Industry, 1931, Mines Branch, Department of Mines, Canada, 55–92 (Plate XXVI).

[2] An Exceptional Increase of Cosmic Rays. *Nature* (March 13, 1943) 151, 308.

[3] G. M. Shrumm and R. Smith: A Portable Geiger-Müller Tube Counter as a Detector for Radioactive Ores. *Canadian Jnl. of Research* (1934) 11, 652–657.

[4] G. M. Furnival: A Silver-Pitchblende Deposit at Contact Lake, Great Bear Lake Area, Canada. *Econ. Geol.* (1939) 34, 739–776.

Reef Prospecting by the Resistivity Method in Uganda

By H. J. R. Way*

(New York Meeting, February 1944)

The work to be described was undertaken at various periods from 1937 to 1939 on the Busia gold field, in the eastern province of Uganda. It was decided to examine the possibility of reef prospection by the resistivity method, for it was not known how far the usually disintegrated nature of most reefs in the ubiquitous laterite near the surface would obscure indications obtained by resistivity traverses. The work at the commencement was therefore largely experimental, but the results obtained thereby were satisfactory, and a survey was started at the Government closed area at Amonikakine.

With the limited time and resources at the writer's disposal, it was not possible to complete the survey to his satisfaction or to follow up exhaustively all the geophysical indications, but some of the results of the experimental work and the survey were of sufficient interest to be worth recording; in particular the relation between the width of reef, electrode separation and shape of the curve, and the interference effect of constant separation curves over zones of float are significant and useful.

Three new veins were located, but only one contained sufficient gold to warrant detailed prospection. This was called the Geophysical reef, and was uncovered over a strike distance of 1140 ft., and there are indications that it extends over a distance of 1990 ft. These results and the recommendations consequent therefrom were embodied in a special report to the Uganda Geological Survey.

History of the Field

The Busia field is in the southeastern corner of Uganda near the Kenya-Uganda border, and is about 17 miles north of the northeastern corner of Lake Victoria.

Gold was first discovered in the area in the stream beds by Davies[1,2] in 1932. Subsequently numerous small alluvial claims were worked by prospectors and the area was prospected for reef by a company for periods varying from three to nine months, but was finally abandoned, as the results were considered unfavorable. Further prospecting by the Geological Survey in 1935-1936 under Davies[3] and later under the writer[4] uncovered three reefs with sufficient gold values to be of economic interest. These were finally taken over by a company known as Borderland Syndicate, which still owns the area, and from September 1937 to the end of 1941 about 13,000 oz. of gold was extracted from reefs of the area proved by the Geological Survey. Opencast mining operations are still proceeding (February 1943). The Amonikakine area lies to the immediate north of that of Borderland Syndicate. A certain amount of prospecting had been done when the writer started work there. As a result of his report, this area was taken over by another syndicate, but little further work was accomplished before it ceased operating because of difficulties of wartime working.

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* Geologist to the Swaziland Protectorate, Mbabane, Swaziland, South Africa.

[1] References are at the end of the paper.

Geology

Briefly, the significant work groups of the area are as follows,[5] in order of superposition:

5. The laterite.
4. The dolerites.
3. The granite and apophyses.
2. The Bulugwe Series.
1. The Tira dolerites.

The Bulugwe series is sedimentary in origin and consists of shales, phyllites and quartzites, all of which have been subjected to movements of an orogenic nature, with the result that the strata are dipping at high angles. The Tira dolerites are associated with the series: their exact age relationship is a moot point, but does not affect the general theory of genesis or the geophysics.

All the preceding rocks have been intruded by the granite and its associated hypabssal apophyses, the local representative of which is a porphyry. The Tira dolerites, usually very fine grained, have been altered at the contact with the granite into a much coarser and more acid type approaching a diorite.

Dolerites in the form of narrow dikes are found frequently cutting the granite and older rocks.

The formation of the laterite is of especial importance and will be discussed later.

The lodes consist of a number of auriferous quartz veins varying from tiny stringers of less than an inch up to veins 10 ft. wide, which are situated in the dolerite, granite and phyllite. The fact that they are always near the granite contact suggests that the mineralization is to be associated with its intrusion. In the unaltered primary zone small quantities of pyrite, arsenopyrite, sphalerite, galena and calcite have been noted in association with the quartz veins. The latter are extremely erratic in their behavior, pinching, swelling and branching both in depth and along their horizontal extensions. They are, however, roughly parallel one to another and always at an angle to the strike of the steeply dipping sediments; i.e., quartzites and phyllites. Where the veins approach the former they tend to pinch out entirely. Probably this is because the fissure system they occupy tends to close in the quartzites. The latter are also mineralized, but their gold content is not as consistent as that in the reefs, and it is doubtful whether they will ever be worked extensively.

The preceding rocks are presumed pre-Cambrian in age by correlation with similar groups in other parts of Africa. They have been subjected to intense peneplanation accompanied by simultaneous decomposition, and lateritization at the surface. These processes have been caused by the peculiar climatic and topographic conditions pertaining to the area at the time of their formation. Large quantities of rain water unable to drain away from the plain have seeped into the underlying rocks, decomposing the constituent minerals and taking iron, alumina and some silica in solution. These solutions have migrated upward during seasons or periods of drought, the movement having been initiated by evaporation at the surface and capillary action in the pore spaces. Precipitation of the solutes near the surface, mostly iron, has been effected by either inorganic or organic[6] chemical reaction. Prerequisites of this type of formation would seem to be alternative periods of intense rainfall and arid conditions, such as are usually the result of tropical or subtropical conditions, together with a large landlocked plain. These conditions must have been widespread in Africa, as similar rock has also been observed in South Africa, and reported from many other parts of the continent.

The processes described have not been absolutely continuous, but have been accompanied by various adjustments such as uplifts and warpings, with the result

that there are at least three peneplains. The one represented in the area under discussion is the lower Peneplain III, thought to be of Pliocene age.

the rises. This type of topography is typical of the mining area, which is situated in the southeastern corner of a vast plain extending about 200 miles to the west

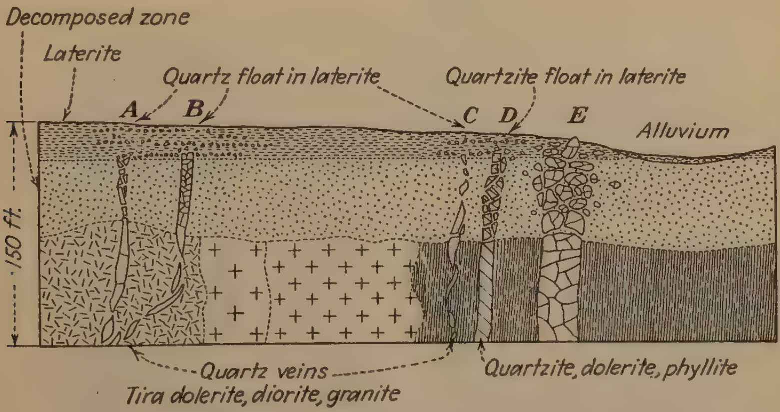

FIG. 1.—SECTION SHOWING GEOLOGY AND MODE OF OCCURRENCE OF LODES.

and an even greater distance to the north. The general drainage of the plain is toward its center, in which are several swamps and swamp lakes through which the Victoria Nile flows on its way to Lake Albert.

These peculiar reactions have formed a gradation of zones passing from extremely hard lateritic ironstone at the surface through a porous, leached, ochreous material, consisting of partially ferruginized and decomposed rock, to decomposed rotten rock and finally to hard, undecomposed rock. The water table usually is just above the last, and if sufficient water is present it may mix with the decomposed rock to form a material of porridge-like consistency, through which it is extremely difficult to sink, and which effectively prevents any deeper exploitation by opencast methods. This material is at a depth of about 70 ft. below the surface.

A point to note with regard to this is that the sheetlike laterite and the formation of zones give a stratigraphical appearance to the geology near the surface, but the zones do not in themselves form homogeneous strata. This pseudostratigraphy is well brought out in Fig. 1.

Since its formation, this lower laterite plain has been subjected to erosion, and shallow valleys have formed, the bottoms of which may be as much as 100 ft. below

It is now necessary to consider the various ways in which the preceding rocks have been affected by the intensive chemical decomposition to which they have been subjected during lateritization. The granites and diorites are extremely susceptible to decomposition on account of their feldspar content. On the other hand, allied hypabyssal types such as dolerites have a considerable resistance to weathering, because of their fine-grained texture, although they are affected by concentrated chemical action such as takes place near the surface. Shales and phyllites are easily weathered, because of their relatively unconsolidated nature. Quartzites and quartz veins are completely resistant to decomposition.

Thus the rocks that resist decomposition are the dolerites, quartzites and quartz veins. All these occur as bands or dikelike bodies in either phyllite or granite. There-

fore they tend to form islands or dikes entirely surrounded by rotten rocks in the subsurface geology, and sometimes even reach the surface, where their outcrops are entirely surrounded by laterite (point *E*, Fig. 1). Although these rocks are resistant to weathering, they are affected by a different factor; namely, physical disintegration. This process is not the usual weathering met with in ordinary subaerial conditions, but a breakdown, which has taken place under the land surface, and has been materially assisted by the chemical decomposition in the country rock. The dolerites are also prone to weather along fractures and fissures. When the lateral support of their host rock is removed by its decomposition, the dike disintegrates and large blocks become detached in the rotten zone. The quartzites and quartz veins are very brittle, not only on account of their inherent properties but because they are rendered porous by the oxidation and leaching of their ore minerals. These rocks, therefore, disintegrate to a greater degree; the break-up usually taking place in the rotten rock.

These masses of disintegrated material, usually termed float, also extend into the surface laterite. It is evident, from the behavior of the quartz float over veins and reefs, that the movements caused by the lateritization have not been entirely vertical. Lateral movements have been caused first by mechanical fall-over on both sides due to disintegration; secondly, by redistribution consequent on the various phases of lateritization, which could not have been entirely continuous. A typical case is shown at *A* (Fig. 1). It should be noted that the float over the solid reef presents a mushroom-shaped cross section. This is a very common phenomenon, frequently noticed in trench excavations. When the float occurs in hard laterite, it tends to become cemented together by the latter to form a compact and hard mass, which simulates a solid reef. This frequently

FIG. 2.—OPENCAST NO. 4 OF BORDERLAND SYNDICATE WORKING QUARTZ FLOAT AND REEF. Surface laterite exposed in far end, right side, and right foreground. White mass on left caused by dropping of decomposed rock in excavation of terraces.

gives a completely erroneous impression of the true width of reef, when the quartz is first exposed by excavation.

A section illustrating the typical geology of the area is given in Fig. 1. The primary zone of undecomposed rocks and their relation to each other are clearly shown. The varying effects of lateritization and disintegration on the reefs, quartzites, and dolerite, as just discussed, are also apparent.

From an economic point of view the effects of the lateritization and disintegration on the reefs are of the utmost importance. By the break-up and leaching of the reefs some gold has been liberated and shed into the surrounding laterite, and also, but to a much smaller extent, in the decomposed zone. But by the oxidation and leaching of the ore minerals most of the gold has been left free in small vugs, fractures and fissures of the remaining broken quartz. These large bodies of float quartz in laterite have been found to contain sufficient gold to be workable by opencast methods. An excavation produced by the workings is shown in Fig. 2. The surface laterite in the terraces at the far end and on the right side can be seen; also a large block of this material in the right foreground. The reef channel, almost vertical, is marked by the deep trench from which it has been extracted in the middle of the pit; the argillaceous nature of the decomposed zone or rotten rock is shown by the mass of white on the left side of the pit; this has been dropped on the side in the process of excavation.

The Geophysics

Apparatus

The instruments used throughout the survey were potentiometer, ammeter, batteries, and commutator, constituting a Gish-Rooney arrangement.[7] The potentiometer was manufactured by Tinsley and Co. of London, S.E., after Broughton Edge's design. It is specially adapted for field use, with an easily removable lid and fits on a specially constructed tripod. It is fitted with a built-in galvanometer and has two circuits, a main and an auxiliary. The main can be standardized accurately and reads from 0.1 to 120 millivolts. The auxiliary circuit cannot be standardized and therefore is not so accurate. It reads from 1 to 220 mv. This circuit is not used unless the reading to be made is above that of the main circuit, and for large readings of this order the small errors of the auxiliary circuit may be neglected. A setup of the instruments is shown in Fig. 3.

Fig. 3.—Setup of instruments on line cut through bush at Amonikakine.
Field potentiometer at left middle, and double commutator at left.

The ammeter and source of the electromotive force, consisting of two 60-volt dry H.T. batteries, were conveniently housed in a strong leather case. The double commutator was manufactured by Evershed and Vignoles, and is similar to that incorporated in their geophysical Megger. It must be rotated at a regular speed for all readings, and introduces a commutator factor into the calculations, which in this case was 0.905.

The Megger could not be used, because the contact resistances varied so considerably within such small horizontal distances that frequently they were above

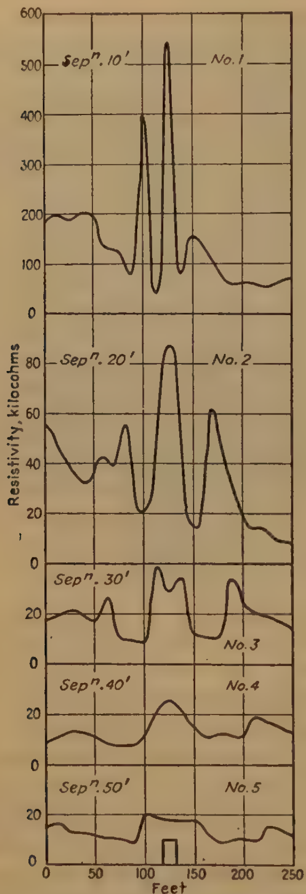

FIG. 4.—TRAVERSE CURVES AT VARIOUS ELECTRODE SEPARATIONS OBTAINED OVER BAUERLE'S REEF.

Width 10 ft. at depth 10 ft. Separation of each curve indicated. Station interval 10 feet.

the range at which the Megger gives accurate readings: values up to 25,000 ohms were sometimes noted. The variation is caused by the thinness of the soil over the laterite; sometimes it is entirely absent. Direct current was used in only a few instances to check the results obtained with an alternating current, as it was found that the nonpolarizing electrodes did not stand up to continuous traversing. After a few days large potential differences developed between pairs, which rendered them inaccurate.

The resistivity units used in the following description are kilocohms, a convenient abbreviation of kilohm-centimeter; i.e., ohm-cm. $\times 10^{-3}$.*

The geophysical results to be described may be divided into two parts: experimental traverses over known reef occurrences, and a resistivity survey over certain regions for prospecting purposes. It is not possible in this paper to give all results in detail, but an effort will be made to describe the most important results, and to show what was achieved by the survey. The four electrodes of the resistivity setup were disposed in a straight line at equal intervals or separations, according to Wenner's system.[8]

Experimental Studies over Known Reef Occurrences

An ideal exposure of reef was provided in two trenches in the Amonikakine area. The reef was uncovered by a prospector named Bauerle, and has been called after him. The reef at the point over which traverses were made is in a condition similar to that of the reef at point *B* in Fig. 1. It was not greatly disintegrated, but extensively fractured and recemented to a hard compact mass to within 2 ft. of the surface by the laterite. The width as exposed in the trenches was 10 ft. at a depth of 10 ft. There was much quartz float in the laterite on both sides of the reef, due to fallover, giving the typical mushroom-shaped cross section mentioned.

The series of traverse curves obtained are given in Fig. 4. They were secured by making traverses at 10-ft. intervals over the reef in a direction at right angles to its strike and at the various electrode separa-

* In the nomenclature accepted by the Institute the kilocohm is equivalent to a decameter-ohm.—Ed.

tions indicated, varying from 10 to 50 ft. These curves are strikingly similar to those that may be easily obtained in a laboratory, under ideal conditions. A suite of such curves was given by H. N. Johnson in discussion of an A.I.M.E. paper.[9] They are reproduced here in Fig. 5, for purposes of comparison. Generally the curve consists of a major maximum immediately over the reef (M) flanked by two minor maxima (m_l and m_r) symmetrically disposed on either side of M. The complex shape of the curve is due to the four point electrodes of Wenner's system, and depends on the position at any point of the four electrodes in relation to the reef, as discussed by Howell.[10]

The basic shape of the curve varies considerably and depends on several factors, the three most important of which are the electrode separation, width of reef, and depth below the surface. The first two factors may be considered together, for it is obvious that if it were possible to vary the width of the reef, and keep the separation constant, the resultant effect must be the same. In other words, an increase in separation is the same in effect as a decrease in the width of the reef, and the actual shape of the curve depends on the ratio between the electrode separation and the width of the reef. For a ratio up to about 2½ the shape of the curve remains much as described, but for larger values the major maximum tends to develop a complex shape by flattening and widening, with the formation of a small minimum at its top, as in curves 3 and 5 of Fig. 4. It is absent in curve 4 of that figure. The size of all three maxima decreases and the subsidiary maxima are further displaced from the center. These tend to vanish if other variations interfere: the result is the formation of a two-maxima type of curve, in which they are symmetrically disposed over the reef.

It is obvious in this field case that the conditions were ideal for resistivity work, as the resistivity of the reef was much greater than its host medium; i.e., laterite or decomposed rock. The maximum values

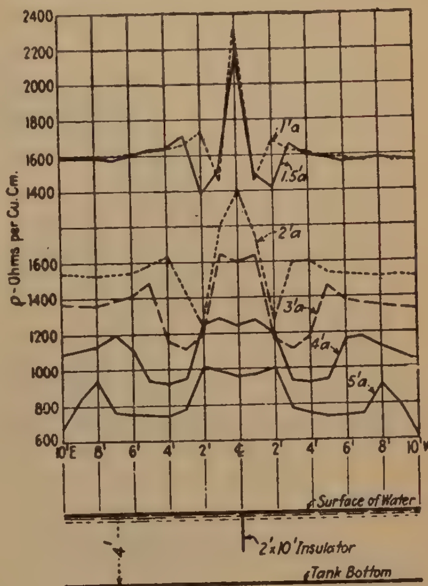

FIG. 5.—PROFILES OVER INSULATOR. (From H. N. Johnson.[9])

over the reef and the laterite for each electrode separation have been plotted in Fig. 6. The value for the laterite has been obtained in each case by averaging the values on the outsides of the minor maxima of each curve. It must be remembered, however, that these values are of apparent resistivity, and therefore are not the absolute resistivity of the laterite, but include whatever rock is present to the depth of the pertinent electrode separation. The resistivity value at 10 ft. should approximate the absolute value of the laterite. The resultant curves in Fig. 6 show that there is a very rapid decrease in apparent resistivity for both media from 10 to 20 ft., and thereafter the decrease is slow. This decrease would be expected in the host medium, for the laterite grades down to decomposed rock. The shaded portion between the curves

gives, at any separation, the difference between apparent resistivity of the reef and host medium. If this difference is compared with the apparent resistivity

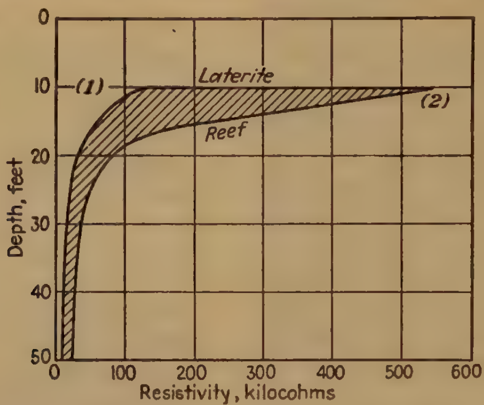

FIG. 6.—APPARENT RESISTIVITY CURVES FOR REEF AND LATERITE PLOTTED AGAINST ELECTRODE SEPARATION OR DEPTH. SHADED AREA GIVES DIFFERENCE.

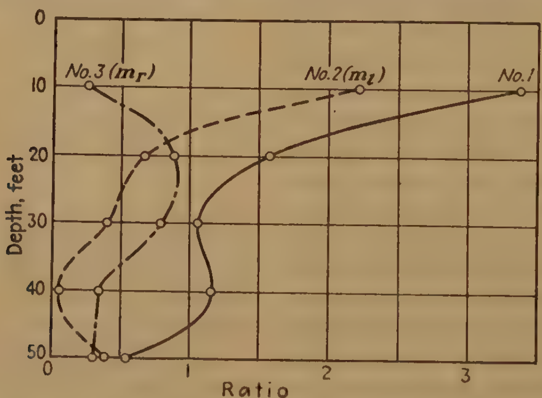

FIG. 7.—SIZE OF ANOMALY (RATIO OF DIFFERENCE TO APPARENT RESISTIVITY OF LATERITE) PLOTTED AGAINST DEPTH (No. 1).
Size of minor maxima of curves over a reef (m_l and m_r) given by Nos. 2 and 3.

of the latter, a ratio is obtained, which gives a measure of the size of the anomaly. This is plotted as curve 1 in Fig. 7. It may be inferred from this curve that the size of the anomaly does not vary much (only between 0.75 and 1) between 30 and 50 ft., but increases greatly from 30 to 10 ft. It may be concluded from this that to obtain a large anomaly in a traverse it is necessary to keep the electrode separation as small as possible.

Johnson's curves (Fig. 5) are all perfectly symmetrical about the major maximum or middle of reef, whereas the field curves obtained by the writer are asymmetrical in the respect that the minor maxima differ in size. This can be shown easily in the laboratory to be caused by the departure of the reef from verticality. The dip of the reef causes an increase in size of the minor maximum on the dip side of the reef, and a decrease in the size of the minor maximum on the other side. The size of m_l and m_r calculated as a ratio as described above, is plotted as curves 2 and 3 in Fig. 7. In three cases

out of five m_r is greater than m_l, therefore the remainder of the data suggest that the reef is dipping to the right, which by referring to the bearings is to the northeast. This point has not yet been settled by further excavation.

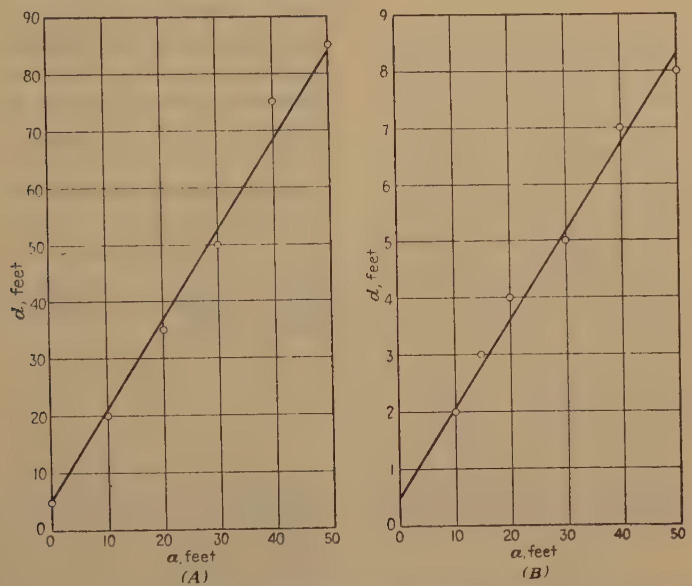

FIG. 8.—d PLOTTED AGAINST a.
Electrode separation or depth for field curves given in Fig. 4 (A); for Johnson's curves (B).

The position of the subsidiary maxima relative to that of M is of considerable interest. In Fig. 4, it is evident that, although the symmetry of the curves is upset by the reef dipping, the actual position of m_l and m_r relative to M remains the same; i.e. equidistant from M. If the distance of either m_l or m_r is denoted by d and plotted against a, the electrode separation, as in Fig. 8, it can be seen that the relation between those two approaches closely a straight-line function, the equation of which is in the form:

$$d = 1\tfrac{1}{2}a + p$$

The similar values from Johnson's curves have been plotted in the same figure, giving much the same result. No doubt, if the curves had been made at closer intervals, all points would lie exactly on the line. Deviations may be owing to the fact that the positions of m_l and m_r have been determined only approximately.

The question now arises as to what the constant p represents. From the equation and graph, it is apparent that it is the intercept made by the function on the d-axis. Has this value any connection with the fundamental properties of the traverse curves? $1\tfrac{1}{2}a$ represents the distance of the current electrode from the center of the electrode system. Thus m_l and m_r are not formed when one current electrode is over the middle of the reef, but at a distance greater than that by the constant p. In the field curves of Fig. 4 the value of p is 5 ft., and this happens to be half the width of the reef. If this deduction is valid, the minor maxima should be formed when a current electrode is over the edge of the reef, and

p may be replaced by $w/2$, where w equals the width of the reef. For Johnson's curves the intercept on the d-axis is $\frac{1}{8}$, and the deducted width of his dike would be 1 ft.

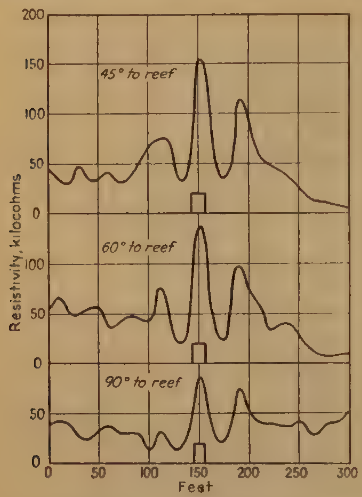

FIG. 9.—EFFECT OF VARYING AZIMUTH ON TRAVERSE CURVES.
Electrode separation 20 ft. Station interval 10 feet.

Unfortunately, the value is not given in the accompanying text. If his sketch is drawn to scale, it would seem that the actual width of the dike is considerably less than that value.

If this relation does hold good, it will be of great importance for use in the interpretation of resistivity curves, as, by making three or more traverses, it should be possible to obtain the width of the reef or dike, if ideal curves are obtained.

The significance of this relationship was not realized while the field work was in progress, but only when all results were being collected together. Thus no confirmatory evidence can be offered at the moment that it holds good for all cases. This is a point that could be settled easily by laboratory work, but the writer has had no opportunity to do this, nor is he likely to have it in the near future.

Three experimental resistivity traverses at an electrode separation of 30 ft. and at intervals of 10 ft. were made over Bauerle's reef to determine the effect, if any, of varying azimuth on the resultant curve. In other words, traverses were made obliquely over the reef. The results are plotted in Fig. 9. The fundamental shape remains unaltered. As the angle between the direction of traverse and the strike of the reef decreases from 90° to 45°, the apparent widening of the reef causes an increase in the size of M.

By arguing from the equation recently suggested,

$$d = 1\tfrac{1}{8}a + w/2$$

it would seem that there should be a small increase in d, for

$$d_{90°} = 35 \text{ ft.}$$

and

$$d_{45°} = 37.1 \text{ ft.}$$

But the increase of 2.1 ft. is too small to show on a curve made at intervals of 10 ft. Actually d from curve No. 1 is 40 ft., which is 5 ft. out. This tends to show that interpretations of width should not be made from curves of one separation only.

In all three curves m_r is greater than m_l, which suggests that the dip of the reef is toward the north-northeast. This substantiates the deductions from Fig. 4.

Deductions from these facts are that even for oblique traverses up to 45° to the reef, the curves retain their characteristic shape, and that the tentative deductions as to the width and dip of the reef may be made from them. This is important, as in making surveys over unknown terrain it may frequently happen that the line of traverse cuts across the reef obliquely. It is pleasing to realize that under such conditions the nature of the anomaly is not destroyed by the obliquity.

Summary of Characteristics of Ideal Resistivity Curves

It has been shown that to obtain a large anomaly on a resistivity curve over a

reef, it is necessary to keep the electrode separation as small as possible; that is, a separation of 10 or 20 ft. would produce the best results, but it is precisely within this depth that the laterite occurs. The inhomogeneity of this rock tends to produce resistivity variations, which become apparent on traverse curves as maxima and minima. It is therefore useful to consider criteria for distinguishing between genuine reef anomalies and those due only to variations in the laterite or host rock. It is possible that cases might occur in which the latter would be indistinguishable from the former, but the chances of that happening are small. The criteria may be summarized as follows: (1) the form or shape, (2) the symmetry, (3) the relation between d and a.

Form or Shape.—It has already been noted that the shape of the curve is not always the same, even in ideal cases, but depends on the ratio of the electrode separation to the width of the reef. When the ratio is from 1 to 3, the subsidiary maxima usually are of sufficient magnitude to be recognized as such, but for greater multiples they are so small as to be easily obliterated by variations in the laterite. Also, the major maximum widens and usually develops a minimum to give a two-maxima type of curve. Such a case may be observed in curve 30 of Fig. 10.

Symmetry.—Although the subsidiary maxima differ in size, they should be equidistant from the major maximum. Unless the traverse is made at very close intervals there is likely to be a small difference between these distances. They should not differ too much, however, otherwise the symmetry would be completely destroyed, and the supposed anomaly regarded with suspicion. In the two-maxima type of curve, they should be symmetrically disposed on either side of the small minimum, which will be immediately over the reef.

Relation of d to a.—In any particular traverse the electrode separation a is known. By using the equation previously suggested, it is possible to estimate approximately the value of d. For example,

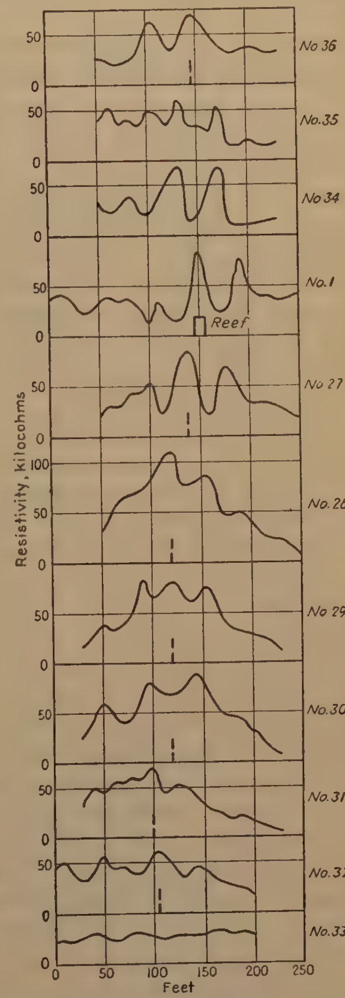

FIG. 10.—TRAVERSE CURVES OBTAINED OVER PRESUMED EXTENSIONS OF BAUERLE'S REEF.

Interval between traverse lines 1-34-36, 20 ft.; 1-27-33, 10 ft. Electrode separation 20 ft. Station interval 10 feet.

with a separation of 20 ft., $d = 30 + p$; for 30 ft., $d = 45 + p$, and so on. If p is small compared with a, it may be neglected; in any case it is possible to

get a rough estimation of what d may be expected to be.

With these criteria in mind it is frequently possible to distinguish false anomalies from true ones.

Departures from Ideal Conditions

The preceding phenomena consist of indications that have resulted from conditions that happened to be perfect. Such conditions are easy to reproduce in the laboratory, but they also sometimes occur in the field; therefore an exact knowledge of them is necessary. For the greater part, however, of field work, conditions are not ideal, and it is now opportune to consider in what way the geological conditions depart from the ideal and how they affect the geophysical results.

The intimate geology of the reef is subject to variations, which, on the whole, tend to militate against the production of perfect resistivity anomalies. The variations that give rise to these anomalies may be classified as follows:

1. Variations in the laterite or decomposed rock.
2. Presence and variation of reef.
3. Presence and variation of float quartz.
4. Presence of other dikelike bodies.

The anomalies that are caused by these variations may be conveniently divided into (1) primary, when the result of difference of rock types b, c and d come under this heading, and (2) secondary, when they are due to the variation within a rock type. Type a falls in this category.

Variations in the laterite are caused by its inhomogeneity, which has already been discussed. Secondary anomalies are produced by it, for they are not due to the presence of other media; in particular, those which are being sought. Such variations may be seen in the portion of the curve No. 2 to the left of m_1 in Fig. 4. These secondary variations, if they are large enough, tend to mask or obliterate the primary anomalies of the reef.

Variations of the decomposed zone between the laterite and solid rock may be mentioned briefly here. Because of its argillaceous nature, its resistivity is low and often is lowered even more by the presence of ground water.[11] No cases of solid reef in decomposed rock without a laterite cover have been investigated, but there is no doubt that they would give very good anomalies, as the resistivity difference between the decomposed rock and reef is large.

With regard to the presence and variation of the reef, as has already been mentioned, it is very often disintegrated within the laterite. What sort of resistivity anomaly, if any, may be expected from such an occurrence? If the solid reef is within the effective depth of the electrode separation of the traverse, it will produce an anomaly that will depart more from the ideal the deeper the reef is from the surface. The subsidiary maxima disappear and the size of the major maximum is considerably diminished. This will vanish entirely when the solid reef is deeper than the effective depth of the measurement. This frequently occurs where the reef is disintegrated in decomposed rock. Such a case is that of No. 33, Fig. 10.

From the consideration of these facts, it becomes obvious that, as the reef becomes solid in depth, the electrode separation should be kept as large as possible, but it has already been shown from other considerations that the electrode separation should be kept as small as possible; for, other things being equal, a smaller separation produces a larger anomaly. It is necessary, therefore, to effect a compromise: under the particular geological conditions pertaining to this area, it was found that a separation of 20 ft. was usually satisfactory. If, however, the resultant traverses proved indeterminant at any point in the survey, further traverses at different separations

were made, provided that sufficient time was available.

In association with most reef occurrences are quantities of float quartz. The variations introduced by it might have been considered with those of the reef itself, as when the reef becomes disintegrated, it is float, but the problem it presents is rather different from that of the variation of the reef. The float varies from quite small to large, roughly lenticular aggregates horizontally disposed over or in the immediate vicinity of the reef, usually, but not exclusively, in the laterite. Johnson[9] has shown that horizontally disposed insulators are capable of producing anomalies, and it has been found that the larger bodies of float also give anomalies in favorable circumstances, which are dependent on the degree of reconsolidation of the float quartz. For example, float in decomposed rock is not reconsolidated, because of the lack of cementing material. The best cementing material is provided by the laterite, especially in the hard zone near the surface, and it is obvious therefore that this is where large, compact, reconsolidated masses of float quartz may be formed.

The anomalies produced by these masses of float are usually in the form of irregular maxima over the greatest thickness. In some cases the float mass is immediately over the reef, and then the anomaly due to it will interfere with that of the reef, causing irregularities to appear in perfect curves. These irregularities are quite unclassifiable, and, if the anomaly of the float is considerably greater than that of the reef, the standard curve may be distorted to such an extent as to be unrecognizable. On the other hand, if the anomaly of the reef is absent, only a simple anomaly due entirely to the float quartz may be present. Distortions in the shape of standard curves may be seen in Nos. 1 and 28 of Fig. 10. In the first case, No. 1, the left minor maximum has almost vanished, whereas a traverse made a few feet away along the line of strike (No. 2, Fig. 4) has a more or less standard

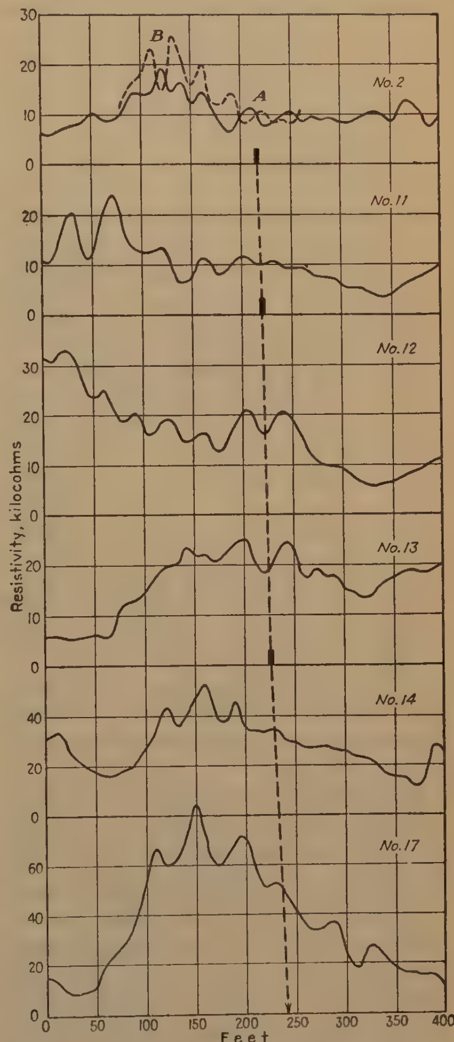

FIG. 11.—SOME TRAVERSE LINES OVER GEOPHYSICAL REEF.

Electrode separation 20 ft. except dotted curve of No. 2, which is 10 ft. Station interval 10 ft. Interval between traverse lines 100 ft. Reef exposed by trenching shown in black. Probable line of reef shown by broken line.

form. In the second case, No. 28, the symmetry is distorted and m_1 is almost nonexistent.

In other cases, as occur most frequently in the field, the float masses are not immediately over the reef, but to one side of it. Two anomalies may be present; one due to the float and one to the reef. Such cases may be observed in Nos. 2 and 11 of Fig. 11.

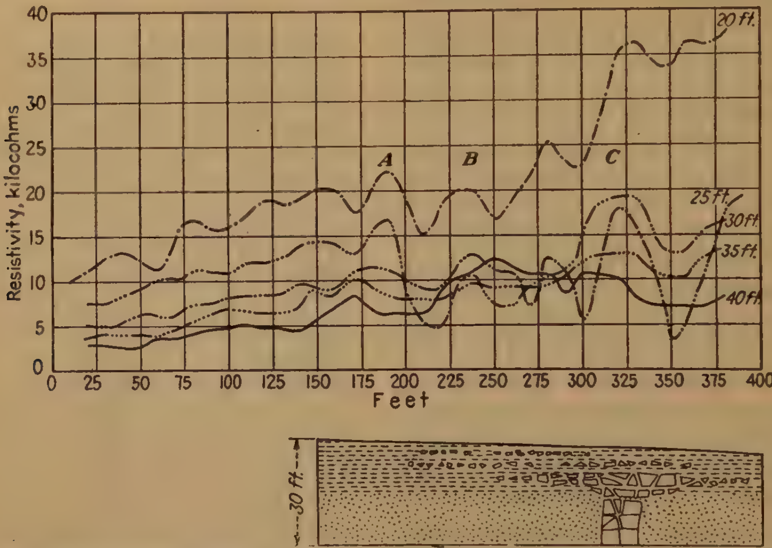

FIG. 12.—RESISTIVITY TRAVERSES OF VARYING ELECTRODE SEPARATION OVER QUARTZITE IN PHYLLITE.

The pronounced interference effect between 200 and 400 ft. should be noted. Station interval 10 feet.

The other dikelike bodies that cause resistivity anomalies in the area are the dolerite dikes and quartzite bands. The latter, although considerably altered by recrystallization and ferruginization, are usually wider and almost always more persistent along their strike than the quartz veins. For this reason the float bodies formed from them are not quite so erratic. The former are capable of giving quite strong anomalies, which are similar in every way to those of the reefs. Fortunately, the quartzites or their related float masses often reach the ground surface, and therefore can be identified as such.

The dolerite dikes usually are much wider than either the quartzites or reefs; at the small separations at which the survey was made, therefore, the effect introduced by them is more a general raising of the average resistivity value of the curve over a considerable distance than the production of a small anomaly. Nevertheless, the fact that sometimes they do occur as narrow dikes and are potentially capable of producing anomalies must be borne in mind. If the presence of large dikes is suspected, it is possible to demonstrate it geophysically by resistivity traverses of 100 ft. separation, as has been shown in connection with water supply.[13]

Some Survey and Prospecting Results

A series of traverses of varying separation were made over the presumed extension of a reef in phyllite on McAllister's claim of the Borderland Syndicate area (Fig. 12).

The gradual gradation from laterite through decomposed rock to solid rock has already been discussed under geology. The fact that the resistivity of the laterite is greater than that of the decomposed

rock gives rise to a gradual decrease in apparent resistivity from the surface down to approximately 50 ft.; the last depending naturally on the depth of the decomposed zone. These variations have been studied in more detail in connection with water supply.[12] It is interesting to note the changes introduced in this gradual decrease by the presence of erratic bodies of float quartz or quartzite in various stages of reconsolidation.

Five resistivity traverses at separations varying from 20 to 40 ft. were made primarily to obtain information over the presumed extension of the reef occurrence in phyllite. The results are given in Fig. 12. Their most pronounced feature is the anomaly at *C*, which on excavation proved to be due to a quartzite band, the exact width of which was not determined. There are smaller anomalies at *A* and *B*, and perhaps yet another between *B* and *C*.

The parts of the curves between 0 and 180 ft. show a most striking parallelism, and if reference is made to the separation of each, it will become apparent that there is a fairly regular decrease in the apparent resistivity from 20 to 40 ft. The remaining portions of the curves, however, show that, although the anomalies roughly coincide on all, they cross each other repeatedly, giving rise to a most pronounced "interference" effect. There is, in fact, no regular decrease in apparent resistivity in that region, and this can be due only to the presence of float bodies. The excavations showed that the horizontal extent to the float roughly coincided with the length of the interference effect; i.e., up to about 110 ft. from the quartzite.

At the completion of the experimental work, when it had been definitely established that resistivity traverses could yield useful information, surveys were started in an effort to locate the extensions of the known reef at Amonikakine, and to investigate the possibility of the presence of others.

Traverses at 10-ft. intervals along a line, at an electrode separation of 20 ft., and at 100-ft. intervals between the lines, were laid at right angles to the strike of the reef. Trenching through the surface laterite was started at any anomaly or indication obtained but sufficient time was not available to follow up all such indications. As a result a new auriferous reef was discovered, and termed Geophysical reef, as well as several bodies of float quartz. A survey was built up over Geophysical reef by laying out traverse lines on either side of each new discovery. Lines usually were made 300 ft. long, but frequently were extended in either direction if the occasion demanded it.

The survey over the presumed extensions of Bauerle's reef is given in Fig. 10. The curves obtained are both interesting and instructive: two of them (Nos. 1 and 27) are almost perfect. No. 28 has become distorted with the left minor maximum absent. No. 30 is the more complicated two-maxima type, with the minor maximum almost absent. It indicates that the electrode separation width of reef ratio is increasing; and as the separation has remained constant, it may be deduced that the width of the reef has decreased; i.e., it must be less than the 10 ft. on line 1. It must also be in a fairly solid condition to produce such a curve. A most interesting type of curve is illustrated by No. 29. This shows three maxima, all approximately the same size. It must be assumed that this represents a transition between Nos. 27 and 30.

From Nos. 31 and 33 it will be observed that the anomaly gradually decreases and finally vanishes, indicating that either the solid reef pinches out or pitches to below 20 ft. Curves 34 to 36 are difficult of interpretation, but No. 34 would seem to be of the two-maxima type with a probable decrease in width of the reef in this direction as well.

Some of the traverses constituting part of the survey over Geophysical reef are given in Fig. 11. It should be noted that the resistivity scales of Nos. 14 and 17 are twice the size of the others and therefore the anomalies on them are correspondingly larger.

The reef was first discovered on No. 2. The resistivity traverse on this line is No. 2 of Fig. 11. Trenches over the anomalies at *A* and *B* yielded a reef with float quartz at *A* and a large quantity of angular blocks of float up to 2 ft. in greatest dimension at *B*. The reef was 4 ft. wide at a depth of 6 ft. and its strike conformed approximately with that of Bauerle's reef. The reason for its producing such a small anomaly proved to be the fact that the reef was considerably disintegrated for the first 6 ft., and had not in this case been reconsolidated by laterite, which here was of more friable nature. Actually, for a width of 4 ft. the separation-width ratio is 5, therefore the curve anticipated would be one of the two-maxima variety, and the reef would be expected near the minimum, as it is. This was further substantiated by a traverse of separation 10 ft., shown by the dotted line in Fig. 11. As this has a lower ratio (2½), it should yield a maximum over the reef. This was indeed obtained, albeit somewhat small. The small maximum over the reef in this curve is accompanied by only one of its satellite maxima, and that is at a distance of 20 ft. to the north-northeast. From the suggested relation it should be 17 ft., giving an error of 3 ft.

As the float quartz at *B* was about 90 ft. away from the reef at *A*, it was at first thought possible that it emanated from a different source, but although the trench was extended in both directions and eventually joined that at *A*, only a small 4-in. stringer was found, and it must therefore be assumed that it has come from Geophysical reef, and serves to illustrate at what distances these float masses are sometimes situated from their parent sources. This, in turn, serves to show that the movements accompanying decomposition and lateritization were not wholly in the vertical plane.

The anomaly due to the reef on No. 11 is extremely small and can hardly be identified as such. This is to be expected, as the separation-width ratio is about 7. The anomaly on No. 12 is quite definite and distinct, and it may be postulated therefrom that the reef widens somewhat on this line. The anomaly on line 13 is also definite and is similar to the previous one. It is a two-maxima type with a suspicion of the minor maxima on either side. Anomalies due to the reef have vanished on lines 14 and 17, indicating that the reef has thinned or pitched out. The anomalies exhibited on these lines are too large to be caused by a reef, but probably are due to either a quartzite band or dolerite dike. It was not possible in the time and with the resources available to trench these locations sufficiently deeply to obtain geological data, but some small quartz stringers were noted near the surface at the point indicated by the arrow on No. 17.

Summary and Conclusion

It has been shown how perfect resistivity curves over reefs are sometimes obtained in the field. An attempt has been made to explain the diversity in their shape and characteristics, which has led to the suggestion of a possible relationship between the electrode separation, width of reef, and a constant of the corresponding curve. It has been further shown how the peculiar geology of the reefs and their associated float masses results in the production of anomalies of various types that depart from the more ideal curves. The terms "primary" and "secondary" indications or anomalies have been introduced to describe those due to differences in rock types and those due to variation of

one rock type, respectively. These results have been used in the prospecting of an area, and have led to the location of a new auriferous reef.

It may be concluded that the interpretation of anomalies of resistivity traverses is by no means a simple matter, but that all aspects of the geology as well as the geophysical problem have to be carefully considered in order to obtain results. It so happens that in this particular field there are numerous reef ramifications running roughly parallel in the country rock, which is in a very decomposed condition near the surface. Associated with bodies of float quartz, the reefs are hidden under no great overburden, which consists of surface laterite. In most places there are no indications of these occurrences at the surface, and it is in such places that resistivity traverses are able to assist in prospecting. Trenching in the hard laterite is a tedious and expensive proposition, as almost everywhere blasting must be used. Thus the cost of covering a large area by pitting and trenching is almost prohibitive. Any method that can cover a given area in a relatively short space of time, and indicates focal points for detailed prospection, is of great value, leading to reduction in cost and a general acceleration of prospecting. Certainly this was achieved by the resistivity method in this case.

Acknowledgment

The writer wishes to express his thanks to Dr. K. A. Davies, Director of the Uganda Geological Survey, for permission to publish this work and for his kindness in correcting the typescript of this paper.

References

1. K. A. Davies: Annual Rept. Geol. Survey of Uganda (1933) para. 79.
2. K. A. Davies: Preliminary Investigations on the Gold Lodes of the Busia Area, Samia County, Eastern Province. Geol. Survey of Uganda, *Bull.* No. 3, para. 305.
3. K. A. Davies: Annual Rept. Geol. Survey of Uganda (1936) para. 25.
4. H. J. R. Way: Annual Rept. Geol. Survey of Uganda (1936) para. 50.
5. K. A. Davies: A Contribution to the Study of the Geology of Kavirondo. Geol. Survey of Uganda, *Bull.* No. 2 (1935) para. 81.
6. A. L. du Toit: The Geology of South Africa, 413. London, 1939. Oliver and Boyd.
7. A. B. Broughton Edge and Laby: The Principles and Practice of Geophysical Prospecting. I.G.E.S. London, 1931, 20.
8. F. Wenner: *Bull.* Nat. Bur. Stds. (1916) **12**, 469.
9. H. N. Johnson: Discussion of Resistivity Surveying in Illinois. *Trans.* A.I.M.E. (1934) **110**, 30.
10. L. G. Howell: Discussion of Resistivity Surveying in Illinois. *Trans.* A.I.M.E. (1934) **110**, 34.
11. H. J. R. Way: Geophysical Prospecting for Water in Uganda. *Mining Magazine* (August 1941).
12. H. J. R. Way: Some Results of the Application of the Resistivity Method to the Water Problems of Uganda. Geol. Survey of Uganda, *Bull.* No. 3 (1939) para. 561.
13. H. J. R. Way: An Analysis of the Results of Prospecting for Water in Uganda by the Resistivity Method. *Bull.* Inst. Min. and Met. (August 1942).

Geophysical Surveys at the Malachite Mine, Jefferson County, Colorado

By C. A. Heiland,* Member, R. M. Tripp,† Junior Member A.I.M.E., and Dart Wantland†

(Chicago Meeting, February 1946)

This paper serves to illustrate the application of geophysics to a virtually abandoned mine property, an application that led to the discovery of an ore body and thus afforded an opportunity to compare subsequent geologic findings with geophysical data.

The work herein described represents, however, more than mere "case history." It demonstrates that it is possible to obtain satisfactory results by simple means and relatively inexperienced personnel. The geophysical surveys were made by students as a part of their field assignments in the course of their regular training, and were supervised by Dart Wantland, J. E. Hawkins and R. Maurice Tripp. In the course of several seasons an appreciable amount of material was accumulated, which gave graduate students an opportunity for special studies. In this connection, the contributions by L. Massé, R. C. Hyslop, and J. E. Hawkins deserve special mention.

The property owners cooperated wholeheartedly in the work, and special thanks are due Messrs. J. F. Johnson and S. E. Zelenkov, of the American Smelting and Refining Co., for their interest and for permission to utilize the results of their development work for this publication.

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Location and Geology

The Malachite mine is situated on the northern slope of Bear Creek Canyon, 4 miles northeast of Evergreen, 1½ miles northwest of Idledale, and 4½ miles west northwest of Morrison, in Jefferson County, Colorado. The location (Fig. 1) is north of the center of sec. 30, T. 45, R. 70 W., at an elevation of about 7500 ft. above sea level. Near the mine the terrain slopes rather uniformly southward at an angle of about 18° (Figs. 3 and 7).

The geology of the Malachite mine area has been described by J. Underhill,[1] W. Lindgren,[2] and J. Boyd.[3,4] A map showing surface outcrops and mine workings appears in Fig. 2.

The Malachite mine is in an amphibolite belt enclosed in gneisses and schists of the Idaho-Springs formation (probably early Algonkian age). The highly contorted beds are nearly vertical and strike slightly north of west. A series of granite-pegmatite dikes have been intruded almost at right angles into the gneisses and schists and doubtedless are postmineral. While most of the formations are exposed at the surface, a part of the slope is covered by slide rock and float, and in the eastern portion by alluvium and creek fill.

A quartz-diorite dike cuts through the amphibolite schists at a small angle with nearly vertical dip. The copper sulphides, developed in this dike by magmatic segregation, occur in lenticular form. As far as the mine workings have revealed, the ore lenses are often discontinuous in depth and

[1] References are at the end of the paper.

along the strike. The ore bodies range in width from 10 to 35 ft. Judging by the magnetic map, they may reach lengths up to 200 ft. or thereabouts, while their ver-

The surface outcrop of the mineralized zone is readily recognized in the field by its highly iron-stained appearance and occasional occurrence of malachite.

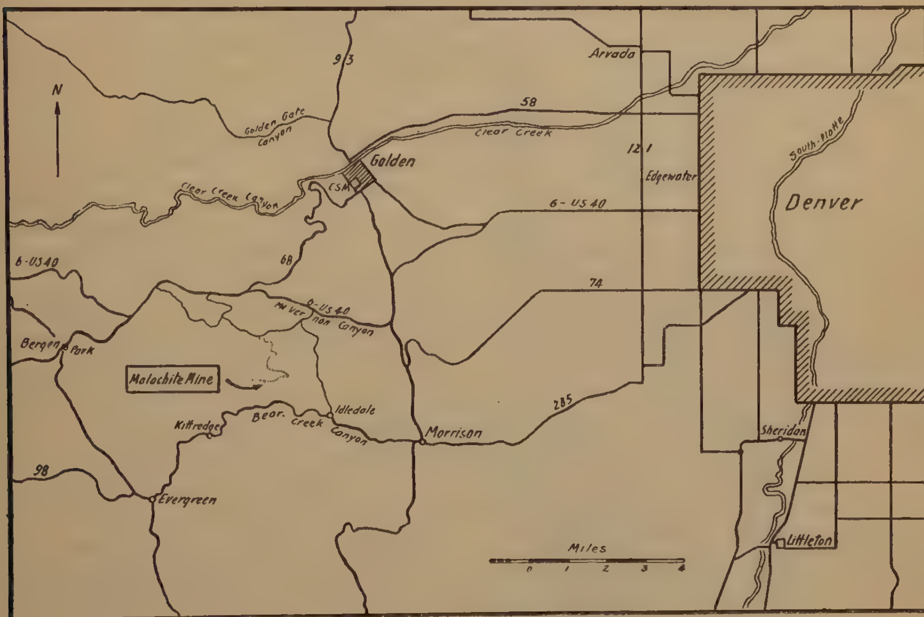

FIG. 1.—LOCATION MAP.

tical extent, on the basis of recent diamond drilling, may be as much as 300 feet.

The ore lenses have been oxidized near the surface and consist there mostly of malachite and azurite. The primary sulphides occur at greater depth; at times, a direct connection between the oxidized and unoxidized portions of the ore is absent. The primary sulphides are massive and consist, in the western ore body, of coarsely crystalline chalcopyrite, pyrrhotite, sphalerite, bornite, pyrite and chalcocite. In the eastern tunnel, the ore is similar except that bornite and sphalerite are absent and cuprite, malachite and azurite are present. It is possible that the eastern ore body is of somewhat different origin from that of the western ore. The gangue minerals are chiefly quartz, andesine, biotite, green hornblende, and minor amounts of titanite, apatite, and microcline.

Along the western edge of the property there is a local abundance of magnetite in the wall rock. Minor amounts of magnetite are associated with the ore in the rest of the area.

HISTORY

The recovery of copper ore from the Malachite mine dates back to the past century. In the period from 1888 to 1893,* a considerable amount of oxidized ore was removed from the eastern part of the property. In 1907, Lindgren[2] reported that the total production up to that time was taken out through a shaft that was 150 ft. deep. A tunnel (designated in Fig. 2 as West Tunnel) was then driven to tap the lower workings at the bottom of the shaft. A branch of this tunnel begins about

* C. W. Henderson, U. S. Bureau of Mines. Personal communication.

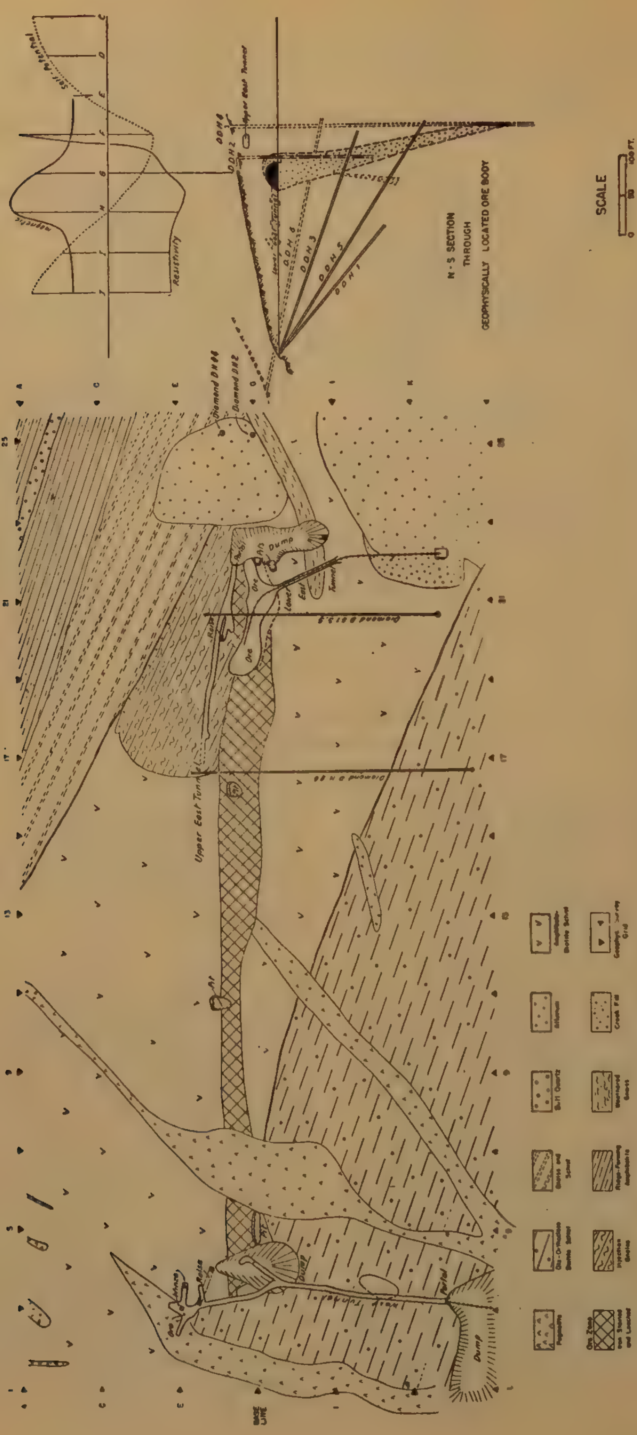

FIG. 2.—GEOLOGY, MINE WORKINGS AND DIAMOND-DRILL HOLES IN MALACHITE MINE AREA.

220 ft. from the portal and runs along a dike in a northerly direction. This tunnel encountered primary sulphides, which apparently had no connection with the oxide ore body worked from the original shaft. Near its end, the tunnel widens considerably into a room from which drifting has been carried on for a short way both east and west along the vein. Two winzes have been sunk in the ore body, one in line with the main tunnel and the other at the end of the east drift. One of the winzes went down 45 ft., at which point the vein had pinched out to about 4 ft. in width. A short distance toward the portal from the stoped-out room, a raise has been driven to the upper workings, which connects to the surface through a shaft. The ore in the upper workings is principally malachite. In the course of the intermittent operations that followed, a two-branched prospecting tunnel (designated as Upper East Tunnel in Fig. 2) was driven approximately along the strike. The northern branch extends about 250 ft. into the hill and has a raise to the surface at a point about 100 ft. from the portal. No primary sulphides were encountered in this drift, which is of interest in connection with what follows:

In the fall of 1937, J. E. Hawkins made a preliminary magnetic survey of the area, outlining the mineralized zone. Although at that time there was doubt as to whether the then-known ore body, being apparently low in pyrite and chalcopyrite, would produce self-potential anomalies, a preliminary survey near the west tunnel revealed disturbances of about 50 mv. near the mineralized zone. In 1938, students of the class in electrical prospecting at the Colorado School of Mines carried on their field work in the vicinity of the old workings at the western end of the property. They found that the self-potential anomalies increased in magnitude toward the east, therefore they extended the work in the following year. A pronounced self-potential minimum was discovered along profile 22, about 1000 ft. east of any known ore. The owners became interested in the results and drove a crosscut northwestward, starting just east of station *I* on profile 22 (designated as Lower East Tunnel in Fig. 2). A massive sulphide ore body was encountered at about 100 ft. from the portal. When mining ceased because of labor shortage, the operations had revealed an ore body approximately 35 ft. wide, pinching out upward in about 15 ft. The eastern limit had been encountered 45 ft. along the strike from the crosscut, and at 120 ft. to the west they were still in good ore.

Apparently the drift adit, driven several years ago westward along the strike from a point between stations *F* and *G* on profile 22 was slightly north and a little above the top of this new lenticular ore mass, as it failed to encounter significant ore.

Figures on ore production resulting from the geophysical discovery are of interest. From September 1940 to March 1941, ore shipped from the Malachite mine totaled 6388 tons. This yielded 244 oz. of gold, 3108 lb. of silver, and 306,000 lb. of copper, at a total value of $44,000. In 1941, the ownership of the property passed from Associated Metals to the American Smelting and Refining Co. By the spring of 1942, this company had completed eight diamond-drill holes with a total of some 2704 ft., outlining the existence of about 34,000 tons of ore assaying 0.05 oz. of gold, 0.90 oz. of silver, and 3.5 per cent copper. Some of the diamond-drill holes are shown in Fig. 2.

Encouraged by the results of the self-potential method, the subsequent electrical prospecting classes have carried the measurements farther east and made resistivity and equipotential line surveys. Magnetic surveys were conducted by J. E. Hawkins, L. Massé, and R. C. Hyslop in 1939, before the discovery cross-cut was completed. In late 1939, J. E. Hawkins

tested his dual-coil electromagnetic ratiometer on the Malachite ore body.

The geophysical survey grid covering the area is indicated by some of its cardinal

FIG. 3.—MAKING MAGNETIC OBSERVATIONS ON SOUTHERN SLOPE OF MALACHITE MINE, LOOKING WEST.

points in Fig. 2. North-south profiles are numbered from 1 to 33 while east west or strike traverses are designated by alphabetical letters from *A* to *M*.

MAGNETIC SURVEY

The magnetic survey includes over 800 vertical intensity stations and about 100 horizontal intensity stations. These were taken with a Schmidt vertical balance (Fig. 3) and a horizontal balance, respectively.

The high magnetic susceptibility of the pyrrhotite produces anomalies of large amplitude in the immediate vicinity of the ore. The magnetically high zone is discontinuous, suggesting the lenticular nature of the ore.

Other minor anomalies appear to be related to magnetite lenses in the gneiss, such as the east-west high in the upper right portion of the area surveyed.

The magnetic properties of the respective formations of the country rock are very similar and no abrupt changes occur when crossing outcrop boundaries. There is, nevertheless, a small difference in the magnetic effects of various formations on the basis of areal averages. Selecting values not disturbed by the anomalies referred to in the preceding paragraph, the following averages result:

Amphibole-biotite schist........	931 gammas
Quartz—orthoclase—biotite schist........................	815 gammas
Ridge-forming amphibolite......	710 gammas

Some of the magnetic anomalies observed over ore lend themselves readily to approximate depth calculations. Assuming, for example, that the magnetic effect along profile 22 (Fig. 5)* is produced by a polarized vertical ellipsoid with one pole far removed, the depth to the upper pole may be calculated to be equal to approximately 39 feet. If the ore body is assumed to be a magnetized vertical plate of infinite strike extent (magnetized line), the depth is calculated to be 30 ft. The average of these values is in agreement with the depth to the top of the stope in the new working, which is about 35 ft. below the surface. The magnetic effect probably results from both the pyrrhotite in the ore and the magnetite in the wall rock; hence the discrepancy between the calculated pole depth and the distance of the top of the stope below the surface is not at all unreasonable. Along profile 20.7 (corresponding to the geologic section shown in Fig. 2) the double half-value distance is 65 ft., which gives 42 ft. for the depth of the magnetic pole and 32.5 ft. for the depth of a magnetized line. Along this line, the

* The maximum anomaly is here about 2100 gammas; the curve was treated as being symmetrical, with a double half-value distance of 60 feet.

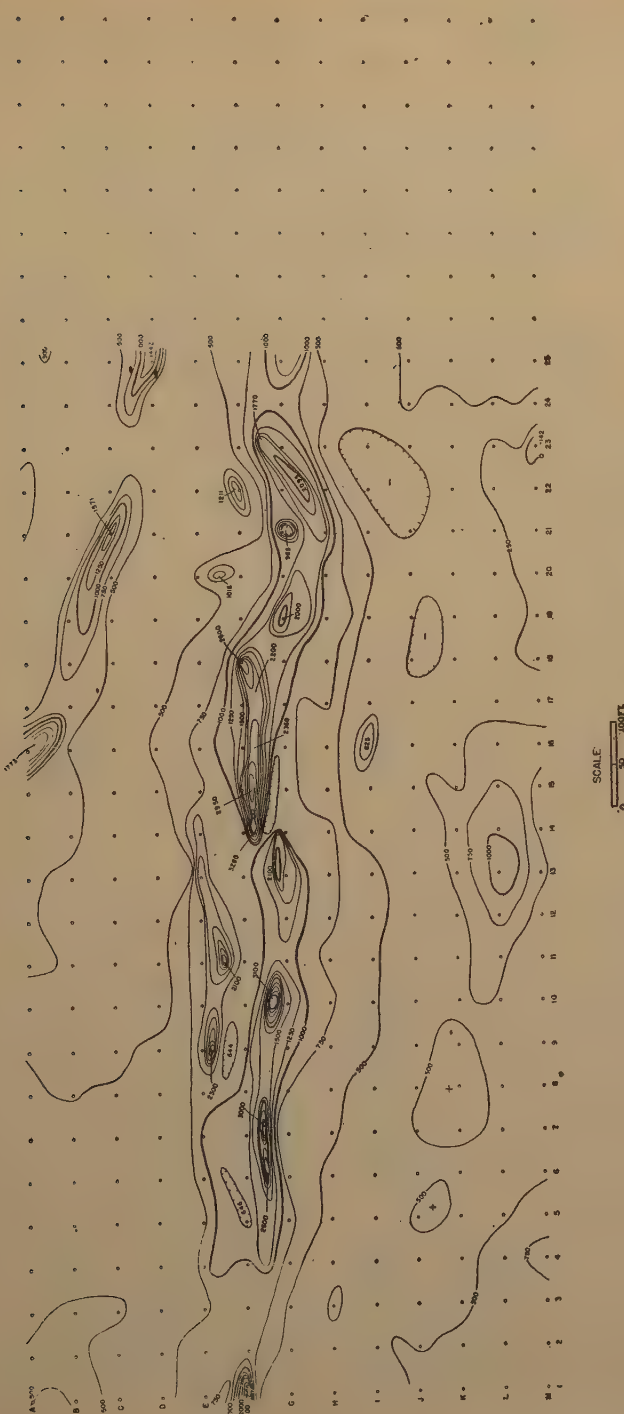

FIG. 4.—LINES OF EQUAL VERTICAL INTENSITY ANOMALY.

depth to the top of the stope is somewhat greater than it is along line 22.

The magnetic profile 22, and particularly profile 20.7, indicate a lesser gradient to the north, which indicates a dip in that direction. As Fig. 2 shows, there is a slight north dip of the ore body with reference to the terrain surface, and the asymmetry of the curve influences, of course, to some extent the accuracy of the depth determinations (which are based on a symmetrical curve of a single pole).

The observations of horizontal intensity just mentioned were made on a number of profiles, and the results, representing their combination with the vertical intensity anomalies in the form of anomalous vectors, are shown in Fig. 5. The depths to the magnetic poles or magnetized lines are indicated approximately by the intersections of the anomalous vectors.

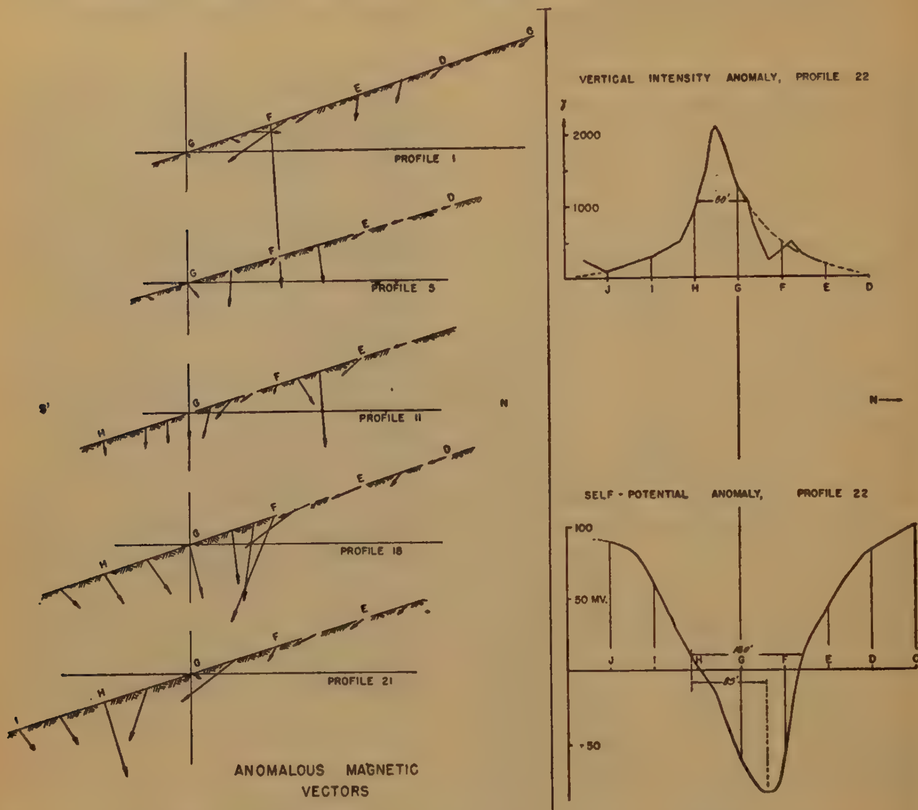

FIG. 5.—ANOMALOUS MAGNETIC VECTORS ON PROFILES 1, 5, 11, 18, AND 21; MAGNETIC PROFILE NO. 22, AND SELF-POTENTIAL PROFILE NO. 22.

SELF-POTENTIAL SURVEY

The self-potential survey was conducted in the conventional manner by measuring potential differences between equidistant points along profile lines at right angles to the strike. Profiles 1 to 18 were run with an electrode spacing of 25 ft. and those from 19 to 33 with a 50-ft. spacing. Several squads worked concurrently with porous pot electrodes and potentiometer. The potential differences were compounded into potential profiles, and from the potential values thus obtained, lines of equal self-potential were drawn. The results appear in Fig. 6.

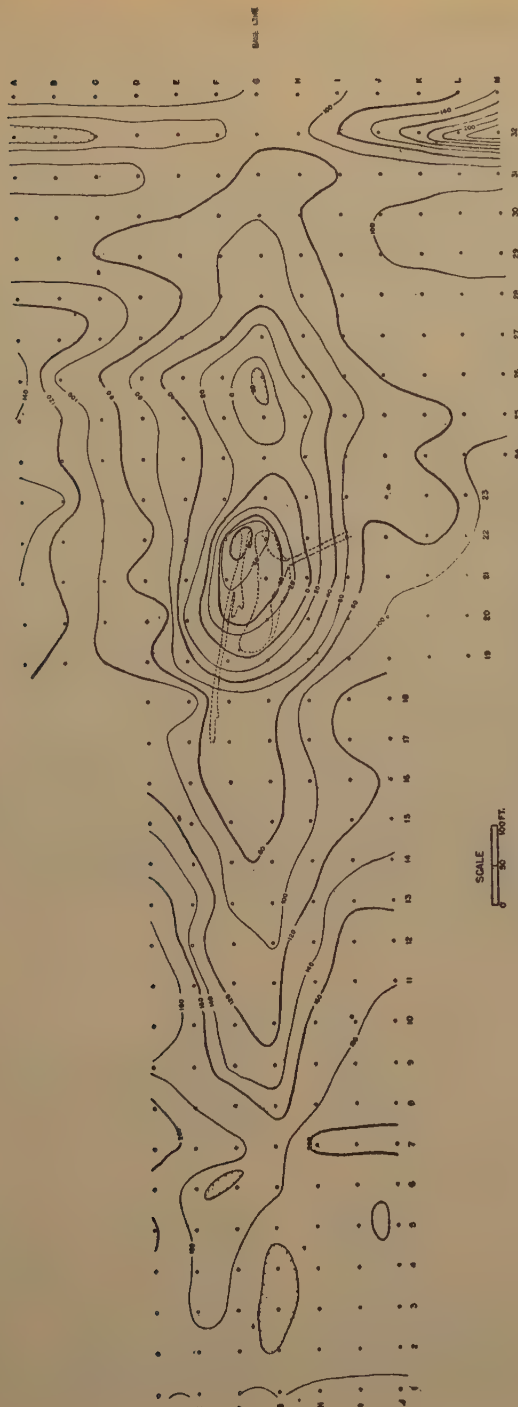

FIG. 6.—ISOPOTENTIAL LINES OF SPONTANEOUS POLARIZATION.

The strike of the mineralized zone has a definite influence upon the trend of the contours. The anomalous zone broadens toward the east—as seen, for example, in the trend of the 80-mv. contour—and culminates in a negative center with an anomaly of minus 80 mv. at the mid-point of profile 22. The larger negative center is slightly north and east of the outline of the new ore body on the lower tunnel level, and appreciably north of the magnetic high and the resistivity low (see Fig. 2). The curve of the self-potential anomaly has its lesser gradient to the south, indicating a dip in that direction, which is the opposite of the effect revealed in the magnetic curve. It is probable that the magnetic (and resistivity effects, see following section) on one hand, and the self-potential effect on the other, are due to different parts of the ore body. In this connection, J. E. Hawkins has pointed out that between the western and eastern workings the magnetic anomalies indicate primarily the strike of the magnetic zone, and the self-potential anomalies, while almost completely absent from the western workings, are strong in the eastern part only and closely related to the position of the ore body. He believes that in the western workings the high vertical intensities are probably associated primarily with pyrrhotite, but this pyrrhotite has not caused large self-potential anomalies; whereas the eastern ore body is high in chalcopyrite, which has produced a comparatively large self-potential effect. This possibility is confirmed by the fact that the ore at the western end of the prospect apparent was higher in pyrrhotite content.

A depth calculation was made from the curve of profile 22 shown in Fig. 5 by assuming the effect to be due to a polarized doublet. The shape of the anomaly contours suggested that such an assumption would be reasonable, although some inaccuracy would be introduced by the asymmetrical nature of the curve. Using one half of the interval between the half-value points in Fig. 5, which is 130 ft., the depth to the center of the doublet[6] figures 85 ft. If the distance between the minimum and the half-value point to the south alone is used (85 ft.), the center of the doublet would be 110 ft. In the anomaly curve of Fig. 2 (corresponding to profile 20.7) the double half-value distance is 156 ft., and this gives 100 ft. to the center of the doublet. These last values seem to be the most reasonable.

An estimate of the upper pole of the doublet can be made by making use of the relation that the potential anomaly is inversely proportional to the first power of distance from a single pole. Hence, the distance between the anomaly maximum and the half-value point would be (for a symmetrical curve) equal to the depth to the pole, multiplied by the square root of 3. Thus, with 130 ft. between the half-value points in Fig. 5, the depth to the upper pole would be 38 ft.; with 85 ft. distance to the half-value point to the south in the same curve, the depth is 49 ft.; finally, along profile 20.7 of Fig. 1, the depth would be 45 ft. In combination with the depth of 100 ft. to the center of the doublet arrived at under the same assumptions as before, the lower end of the ore should be expected at about 155 ft., which is not unreasonable, although less than the depth indicated by the drill holes (for a pinching out body).

The depths to the upper electrical pole indicated by the self-potential curves, on the whole, are somewhat greater than the depths indicated by the magnetic anomalies.

Resistivity Measurements

The resistivity measurements were confined to an area between profiles 19 and 28. A Gish-Rooney electrode arrangement (Fig. 7) was used with a fixed spacing of 50 ft. for resistivity mapping. Values of apparent resistivity were plotted midway between the potential electrodes.

The results, shown in Fig. 8, conform very well to the magnetic and self-potential data. A resistivity low occurs between profiles 22 and 24 and extends from line *H* on profile 22 almost to line *F* on profile 24. The location of this low agrees well with that of the magnetic high. Like the latter, it is displaced downslope and to the east with respect to the position of the new ore body, where it is intersected by the lower tunnel level.

Another resistivity low appears downslope to the south near the alluvial fill. This second low may be due to the accumulation of sulphate ions from the oxidized portion of the new ore body, which were leached from the mineralized zone higher up and were concentrated in the alluvial beds.

The very high resistivity values along profiles 20 and 21 in the gneiss and schist areas to the north of the new ore body confirm the belief that the magnetic high in this area is probably due to a magnetite lens in the schist and is not related to ore mineralization.

The low at the north end of profile 25 is associated with a seep spring produced by the damming of the subsurface drainage by the nearly vertical and impermeable amphibolite beds striking normal to the small valley on the east side of the area.

In order to determine the approximate depth to the ore body along the conductive zone previously referred to, a setup was made near profile 22 with electrode intervals increasing from 5 to 70 ft. The apparent resistivity plotted against electrode

FIG. 7.—SETUP FOR RESISTIVITY MAPPING ON SLOPE OF MALACHITE MINE, LOOKING SOUTH TOWARD BEAR CREEK CANYON.

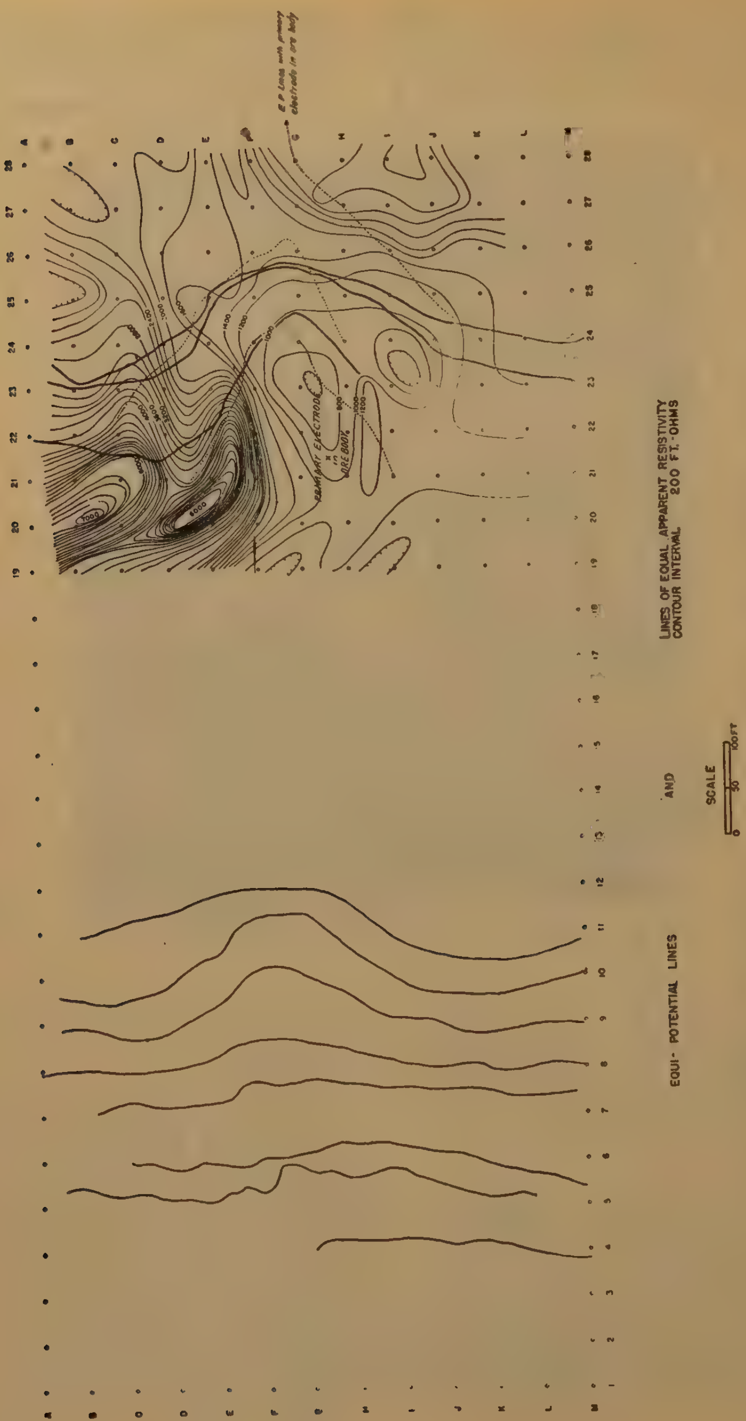

FIG. 8.—EQUIPOTENTIAL LINES AND LINES OF EQUAL APPARENT RESISTIVITY.

spacing yielded a curve having an intermediate surface resistivity of about 850 foot-ohms, which increased to 1125 foot-ohms at an electrode separation of 15 ft., then dropped rapidly until the separation reached about 45 ft., where the resistivity began to reach a constant value of about 725 foot-ohms. The Tagg method of interpretation yielded a figure of 27 ft. for the depth to the conductive zone, which is less than the depth determined from the magnetic data but still in good agreement with it. In fact, the agreement is probably fortuitous, since the theory of the Tagg interpretation is based upon the assumption of horizontally stratified semi-infinite media.

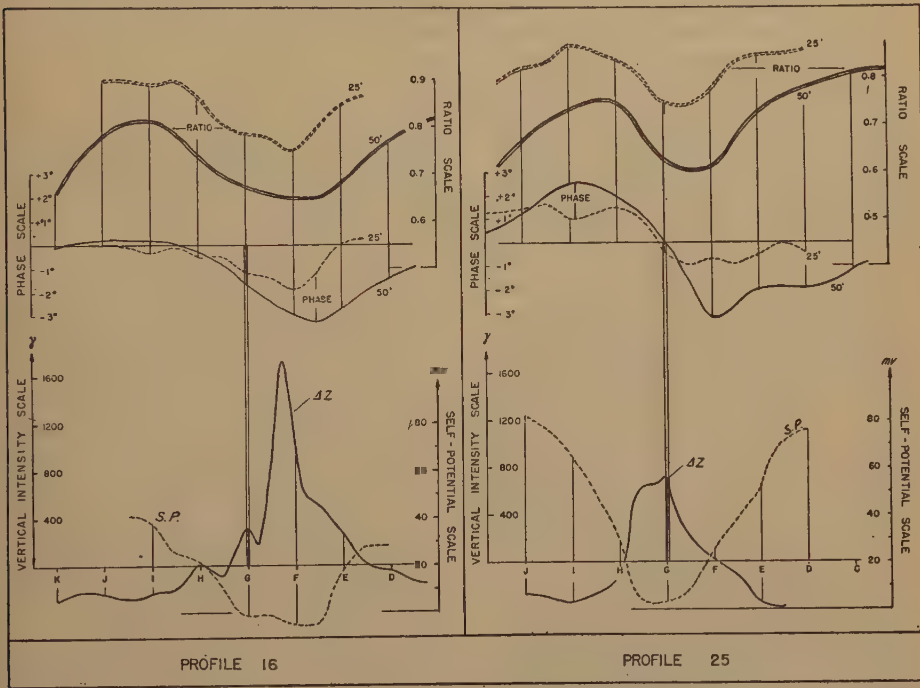

FIG. 9.—PROFILES OF INTENSITY RATIO AND PHASE-DIFFERENCE PROFILES OF ELECTROMAGNETIC FIELD.

EQUIPOTENTIAL-LINE SURVEY

A number of equipotential lines were mapped with the conventional equipment, mainly to get a general idea about trends rather than with the objective to make a detailed survey. The few lines that were mapped are indicated in Fig. 8. The ground was energized by two line electrodes extending along profile 4 and profile 26. Although the survey is very sketchy and limited to a small area, the general trend of the lines substantiates the information obtained by the self-potential and resistivity surveys. It is noteworthy that a topographic effect is absent, largely because the mine is on a uniform slope.

The ease of access to the ore body opened up as a result of the earlier geophysical surveys offered an opportunity to survey equipotential lines with one of the primary electrodes grounded in the ore body, whereby, theoretically, the body itself becomes an equipotential surface whose shape is then reflected in the surfaces or lines respectively surveyed some distance from it. Only a few such lines were sur-

veyed; they are indicated by dots in Fig. 8, together with the position of the primary electrode in the ore body. The trend of the lines does indeed follow the outline of the ore body toward the east to some extent; moreover, it also coincides well with the trend of the lines surveyed with line electrodes outside the ore body. It is probable that an effect of anisotropy in the surrounding formations, which distends the equipotential surfaces in the direction of strike, is superimposed upon that of the ore body itself.

Electromagnetic Field Observations

In connection with tests of a dual-coil field ratiometer, J. E. Hawkins[5] ran two profiles across the mineralized zone. A cable about 1750 ft. long was laid out along transverse line *M* and grounded at profile lines 2 and 35. Ratios of vertical intensity and phase differences of the electromagnetic field were determined along profile lines 16 and 25 with 25 and 50-ft. coil separations (Fig. 9).

Distinct anomalies were observed in both intensity ratio and phase difference, although both profiles are some distance away from the ore body. As should be expected, the indications obtained with the large spacings are somewhat broader and have less definition. Both types of anomalies, however, occur in close relation to the magnetic and electrical (spontaneous polarization) anomalies on the same profile lines. The agreement with the latter is somewhat better that with the magnetic data, the magnetic highs being some distance to the south of the electrical indications, as was mentioned before.

References

1. J. Underhill: Areal Geology of Lower Clear Creek. *Proc.* Colo. Sci. Soc. (1906) **8**, 103–122.
2. W. Lindgren: Notes of Copper Deposits in Chaffee, Fremont, and Jefferson Counties, Colorado. U. S. Geol. Survey *Bull.* 340 (1908) 167–170.
3. J. Boyd: A Preliminary Study of the Pre-Cambrian Ore Deposits of Colorado. Colorado School of Mines, M.S. Thesis (May 1932) 45.
4. J. Boyd: The Pre-Cambrian Mineral Deposits of Colorado. Colorado School of Mines, D.Sc. Thesis (May 1940) 52.
5. J. E. Hawkins: The Design of a Dual Coil Ratiometer Suitable for Geophysical Investigations. Colorado School of Mines, D.Sc. Thesis (May 1940) 36–39.
6. C. A. Heiland: Geophysical Exploration, 673. New York, 1940. Prentice-Hall, Inc.

A Geological and Geophysical Study of the Chelan Nickel Deposit, near Winesap, Washington

By Ernest N. Patty* and Sherwin F. Kelly,† Members A.I.M.E.

(Chicago Meeting, February 1946)

The present case history deals with the examination of an almost forgotten nickel prospect, near Winesap, Chelan County, Washington. Although the final results yielded no ore body of commercial importance, the integration of surface and underground exploration, geophysical survey and diamond drilling endow the story with interest. The program is significant because it is illustrative of how the most disappointing expenditures in mining exploration, the "not-finding" costs, could have been reduced had geophysical methods been applied at an appropriate stage in the prospecting work.

The Chelan nickel deposit was discovered about 1900, on a sage-brush-covered hillside with a southerly slope, adjacent to Winesap Canyon; the paved highway now extending from Wenatchee northward, up the Columbia River and into Okanogan Valley, is only a mile away. After the deposit was found, three short prospect tunnels were driven into it, and the prospect then remained dormant for 40 years. No. 1 tunnel was 80 ft. long, running north into the hillside. For the first 35 ft. this adit exposed a typical, iron-stained gossan with streaks and stains of malachite, and small seams of water-soluble nickel sulphate. Beyond this, it encountered a relatively fresh peridotite, well mineralized with blebs of pentlandite. Systematic sampling yielded an average assay of 1.5 per cent nickel and 0.3 per cent copper. Down the hillside to the south and 35 ft. lower in elevation, No. 2 tunnel was driven under No. 1 and in the same direction, traversing 50 ft. of gneiss before it reached the peridotite. At this point the latter formation showed only scattered blebs of sulphides, not of commercial grade. To the west, on the same contour line as No. 1 tunnel, and 800 ft. around the hillside from it, No. 3 tunnel was driven 50 ft. into the hill to explore a strong gossan outcrop that assayed 0.5 per cent nickel (Fig. 1).

From the geological exposures on the hillside and in the tunnels, it appears that the main mass of the hill is formed of an ancient and altered gneiss complex. Into this, a sill-like injection of amphibolite (altered peridotite) was intruded, which, at least in some places, contains commercial quantities of nickel sulphide. Its structure is obscure, but it appears to dip into the hill at an angle of about 15°. In the vicinity of No. 3 tunnel a large dike of quartz diorite cuts the peridotite or amphibolite; about 140 ft. north of the portal of the tunnel, a dike of andesite 90 ft. wide cuts boldly up the hillside to break the continuity of the peridotite in that direction.

The geological evidence available was not adequate to decide whether the peridotite forms a continuous sill, or occurs as isolated bodies in the gneiss. Not all of this peridotite carries commercial amounts of pentlandite, but if the mineral-

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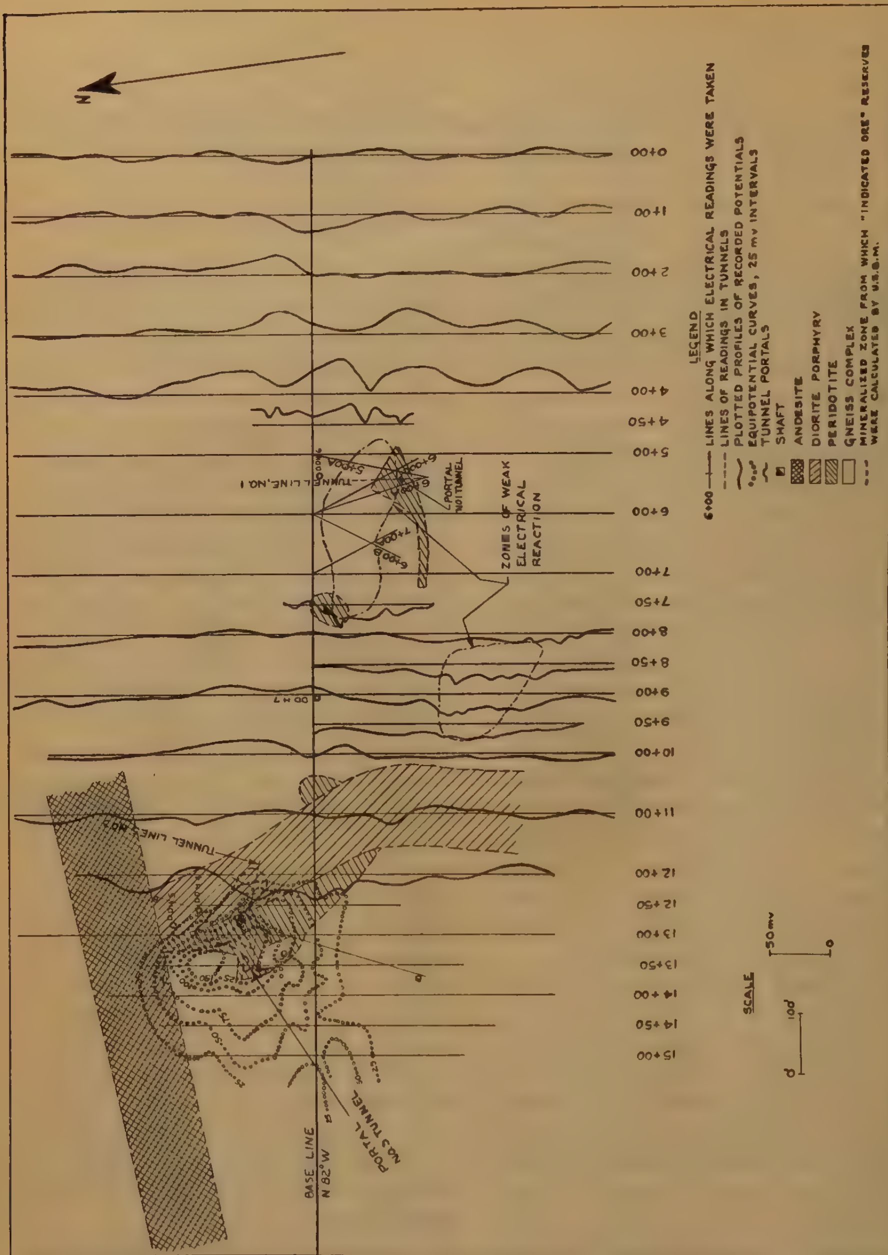

FIG. 1.—SURFACE PLAN: GEOLOGY AND GEOPHYSICAL SURVEY, CHELAN NICKEL PROSPECT NEAR WINESAP, WASHINGTON. Surface geology courtesy of U. S. Geological Survey.

ized section of this formation extended all the way from No. 1 to No. 3 tunnel, a commercial ore body might be anticipated. To check this possibility a large number of open cuts and test pits were recently put down through the deep overburden of the hillside. Although many of these pits disclosed the altered periodotite or amphibolite, nickel mineralization was found at only a few points. The results of this test

pitting were discouraging, but the strong gossan exposure at No. 3 tunnel could not be disregarded, so this tunnel was continued into the hill, and shortly broke into fresh sulphides averaging 1.5 per cent nickel and 0.3 per cent copper. Branches of the tunnel were driven, which outlined an elliptical body of ore 200 ft. long, and 30 ft. thick (measuring about 120 ft. wide on the horizontal). Then the various headings from No. 3 tunnel started running out of commercial ore in every direction.

FIG. 2.—SPONTANEOUS POLARIZATION EQUIPMENT IN USE ON CHELAN NICKEL SURVEY.

CHOICE OF GEOPHYSICAL METHOD

At this point in the exploration program it was decided to make a geophysical survey for the purpose of determining, first, whether the showings in the vicinities of No. 1 tunnel and No. 3 tunnel were separate or constituted two exposures of a single, continuous band, which had been missed in the test pitting; and second, whether the ore exposed in No. 3 tunnel had any extensions, or neighboring sulphide lenses. The following factors influenced the choice of geophysical technique best adapted to answering these questions.

Although pyrrhotite accompanying the pentlandite would yield a magnetic reaction, similar anomalies due to the amphibolite would almost certainly becloud the results. Furthermore, sulphides containing little or no pyrrhotite would give no magnetic indication of their presence, rendering the magnetic results worse than useless under such circumstances. For these reasons the magnetic technique was ruled out.

Although electrical resistivity measurements would show zones of low resistance over sulphide mineralization, wet faults and shear zones would also produce similar anomalies, with consequent confusion in the interpretation of results; this method was therefore eliminated.

The spontaneous polarization method was decided upon as being the most direct and simple procedure for obtaining the desired information. This method, sometimes called the self-potential technique, is direct and rapid; it relies upon detecting, at the surface of the ground, those electrical currents that are spontaneously generated by sulphide mineralization, as a result of electrochemical reactions between the sulphides (metallic conductors of electricity) and the adjacent ground moisture (electrolytes). Readings were taken at 50-ft. intervals along profile lines spaced 100 ft. apart, and cutting across the strike of the mineral-bearing formation. For greater detail, some readings were taken closer, even

at 5-ft. intervals; lines of observations were also run in No. 1 tunnel and No. 3 tunnel. The locations of the profiles thus read are shown on Fig. 1. An area about 1500 ft. east and west by 1000 ft. north and south was thus surveyed by the spontaneous polarization method in 1944.

The equipment is shown in Fig. 2.

Results of Geophysical Survey

The results of the geophysical survey are depicted in two ways on the accompanying maps (Figs. 1 and 3 to 5). First, the readings taken along a profile line are plotted against the corresponding observation stations. Since the point of primary interest is the magnitude of the electrical activity over the apex of the sulphide body, which is the negative pole of the battery, or point of inflow of the current from the surrounding rocks, the negative potentials are plotted *above* the line. The resultant profile of electrical activity therefore rises to a peak over the causative sulphide mass. Second, a series of related profiles, usually along parallel lines, can be used to construct a map of equipotential curves. Each equipotential curve joins the points that are at the same potential, or electrical level; they may thus be thought of as the contour lines of the mountain of electrical activity centered on the sulphide body. In the vicinity of tunnel No. 1, only the profiles were plotted, because the activity is too weak and irregular to justify drawing in the equipotential curves. In the vicinity of tunnel No. 3, both the observed profiles and the equipotential curves drawn from them are shown.

During the geophysical work three areas of electrical activity were recorded, only one of which was of important magnitude. They are all of interest, however, because the reactions observed are typical of different modes of sulphide occurrence. Examples are found of reactions indicative of low sulphide content in a broad zone, of very small pockets of stronger sulphide mineralization, and of a moderately large body of fairly good sulphide content.

The area in the immediate vicinity of tunnel No. 1 exhibits a very weak electrical activity, which in this instance, may be ascribed to the presence of sparsely disseminated sulphides. The maximum potentials observed at the surface, of the order of only 25 millivolts, were in a zone about 150 ft. wide, extending south from the base line between profiles 5 + 00 and 7 + 50. The appearance of the electrical profiles suggests that the strongest mineralization will be found between lines 5 + 00A and 6 + 00. The maximum width of the band is nearly 150 ft. on profiles 6 + 00, 6 + 00A and 6 + 00C, and then narrows east and west, to pinch out between profiles 4 + 50 and 5 + 00 on the east, and between 7 + 50 and 8 + 00 on the west. The detailed readings taken along the profile lines in this zone are shown in Fig. 3, where the profiles have been plotted as though they were all parallel, in order to avoid confusion of intersecting lines.

The weak electrical reactions just described are of the order of magnitude of those which can be produced by formational contacts, or by purely superficial effects. In the present instance, however, the resulting minor irregularities in the electrical profiles offer some contrast with the flatter appearance presented by those in the surrounding area. This, combined with the fact that the known occurrence of sulphides here provides a basis of correlation, is the only excuse for drawing conclusions from their general appearance. On this basis, they are taken to indicate a small region in which the average sulphide content is very low, probably less than 5 per cent. Irregular and pockety occurrences of slightly stronger mineralization are responsible for the individual peaks.

Tunnel No. 1 penetrates the hillside beneath this zone of weak electrical activity, and the observations made in it provide an interesting comparison with

the readings at the surface. About 50 ft. in from the tunnel portal a peak of nearly 150 mv. was recorded (Fig. 3). The acute shape and narrow base of the plotted mineralization. These bodies will be small and of irregular occurrence, and are too limited to produce distinctive reactions at the surface. It is therefore possible that

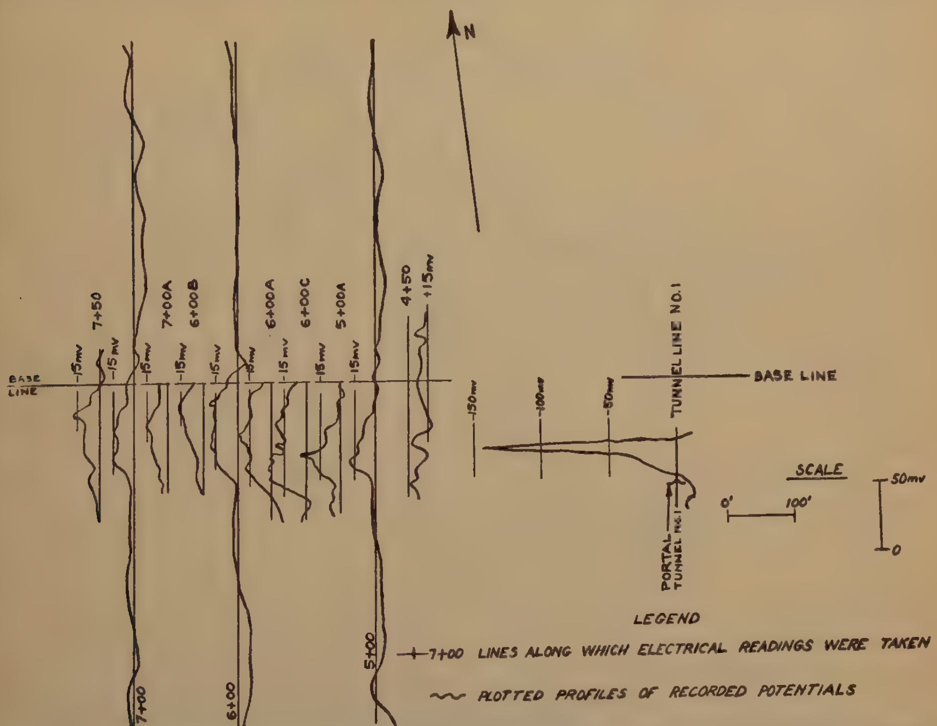

FIG. 3.—DETAILS OF SPONTANEOUS POLARIZATION PROFILES NEAR TUNNEL NO. 1, CHELAN NICKEL PROSPECT.

readings are striking, and are typical of the reaction set up by a sulphide pocket of extremely limited vertical extent. At the surface of the ground on profiles 5 + 00A and 6 + 00C, are two small electrical peaks approximately above this tunnel reaction, which demonstrate that even a shallow overburden (10 to 15 ft.) nearly masks the electrical activity of this small sulphide pocket, reinforcing the conclusion that its vertical extent is insignificant.

The deduction to be drawn from these phenomena is that this zone of low average sulphide content may yet contain small pockets of appreciably stronger sulphide such insignificant blebs may occur with sufficient frequency to "sweeten" slightly the average sulphide content.

It is probably just such a small sulphide pocket that yielded the favorable assays recorded in tunnel No. 1. In the samples taken between 35 ft. and 50 ft. in from the tunnel portal, the assay figures for copper and nickel are in general somewhat higher than elsewhere in the tunnel. This would imply that the sulphide content is somewhat higher here, which is also the zone in which the maximum potentials were recorded on the line of readings in the tunnel. Since the electrical reactions elsewhere in this general region indicate

a lower average sulphide content, it is reasonable to assume that the copper-nickel content would also be lower.

Just east of this area of weak negative potentials there lies a zone of equally weak positive potentials, where a draw cuts back into the hillside. This could be due either to a fault which serves to conduct the outflowing current from the lower part of the sulphide body to the surface, to a forma-

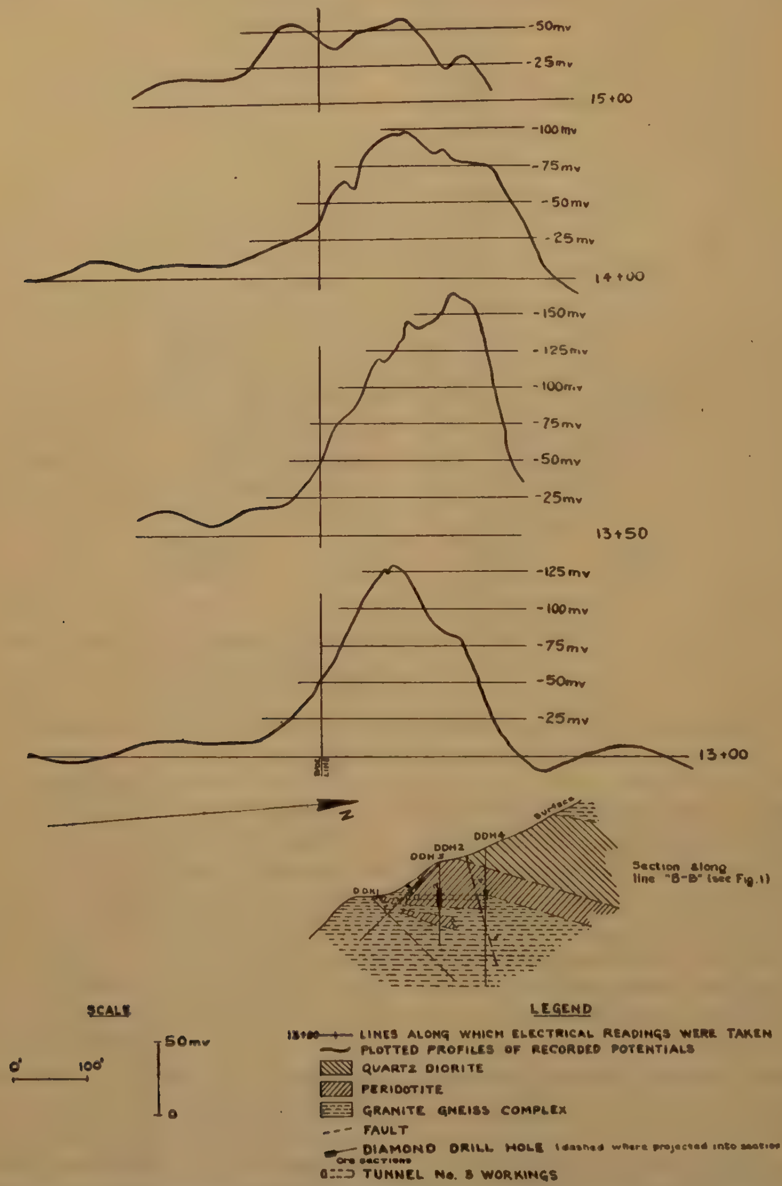

FIG. 4.—SPONTANEOUS POLARIZATION PROFILES AND DRILL DATA AT TUNNEL No. 3, CHELAN NICKEL PROSPECT.
Drill data courtesy of U. S. Bureau of Mines.

tional contact, to purely superficial effects or to the sulphide mineralization extending to such a shallow depth that the draw approached close enough to its lower

No. 3 tunnel, and that the sulphides encountered in those two tunnels have no connection near the surface. On the basis of this geophysical deduction, the cost of

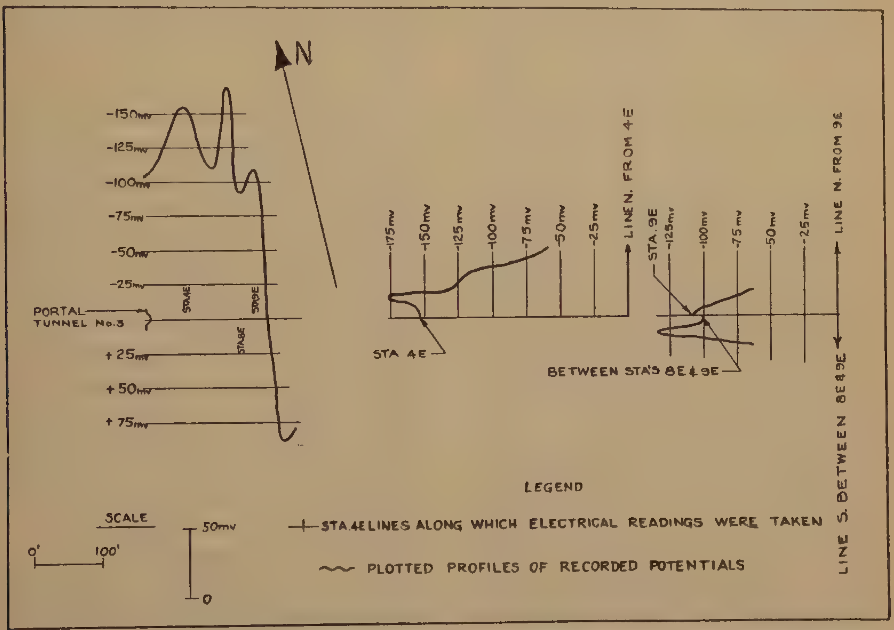

FIG. 5.—SPONTANEOUS POLARIZATION PROFILES IN TUNNEL NO. 3, CHELAN NICKEL PROSPECT.

portion to encounter the weak positive potentials associated with the bottom of a sulphide formation. In any event, the ore exposed in No. 1 tunnel is an isolated, mineralized area of very limited extent, both horizontally and vertically, carrying only weakly disseminated sulphides.

The deductions drawn from the surface geophysical survey would most assuredly not have warranted the expense of driving any adits into the hillside at this point.

The only electrical activity ascribable to sulphide mineralization between No. 1 tunnel and No. 3 tunnel was found on profiles 8 + 50 to 9 + 50. The potentials are even weaker than in the vicinity of tunnel No. 1, so this small area could be ruled out from the point of view of commercial interest. The geophysical survey therefore indicated that there is no mineralization between No. 1 tunnel and

test-pitting the hillside could have been obviated.

The only interesting area of electrical activity discovered in the course of this survey is in the vicinity of tunnel No. 3. It extends from profile 12 + 50 to profile 15 + 00, and for a maximum width of 300 ft. north from the base line. The profiles of the electrical potentials observed here contrast strongly with those recorded in the first zones described; see Fig. 4. The peak reactions are from 125 to 150 mv., and the plotted curves, with their broad bases, make a striking contrast to the type of reaction recorded near tunnel No. 1. The fact that the electrical activity in the vicinity of tunnel No. 3 is spread over a width of 200 to 300 ft. is indicative of a fair extension in depth of the causative sulphide mass, or masses. The alignment of the points of maximum reaction implies

the presence of two bands of sulphide mineralization, or one band with heavier streaks on the hanging wall and footwall.

The electrical readings taken in tunnel No. 3 provide an illuminating comparison with those taken in tunnel No. 1 (Figs. 3 and 5). It will be recalled that in tunnel No. 1 an acute peak of nearly 150 mv. was well-nigh masked by the overburden, so that only very minor activity was recorded at the surface above it. In tunnel No. 3, however, a peak of over 150 mv. occurs at station 4E, almost immediately below one of 130 mv. on profile 13 + 00. The electrical activity from the underlying sulphide body is so well spread through the country rock, by reason of the depth to the positive pole of the body, that the overburden reduces this peak hardly at all. The same observation applies to the peak of 175 mv. on the line north from station 4E, and the surface maximum of 125 to 150 mv. above it.

The individual potential maxima read in these tunnel lines are probably due to local concentrations of sulphide mineralization, and the saddle 40 ft. east of station 4E, between the first two maxima, coincides with a low-grade zone. The plotted curves show a good width and rounded outline entirely lacking from the profile read in tunnel No. 1, all of which points to a stronger and deeper sulphide mineralization in the vicinity of tunnel No. 3.

A striking feature of the profile read along the main tunnel is the pronounced development of positive potentials at the eastern end of the line. The last two readings were in the quartz diorite dike, much broken by faulting and the third from the last reading was close to a fault zone bordering the dike. It seems probable that the positive potentials recorded are the result of a current flow through the faulted dike and shear zone toward the surface, from the positive pole of the sulphide body lower down the dip.

In sum, the electrical activity recorded in the vicinity of tunnel No. 3 implies a small, moderately strong sulphide mineralization, with some extension in depth. A band of sulphides probably 200 ft. or so long and about 60 ft. wide is indicated, with the surface trace striking between N. 35° W. and N. 77° W. The results point to two bands of mineralization, or a single band with heavier mineralization along the footwall and hanging wall, but of limited horizontal extent. The appearance of the electrical profiles suggests a northeast dip for the sulphide mass. Preliminary drilling, based on geophysical results, could have yielded information indicating the best places at which to carry out further investigations. Some tunneling might have been required before finally condemning the deposit, but the cost of test pitting and much of the expense of tunneling could have been saved, as was demonstrated by subsequent events.

Work by Bureau of Mines

The geophysical work confirmed the deductions drawn from the results of the previous prospecting work, and also revealed no reason to anticipate additional, or better mineralization in the vicinity. The owners therefore decided to spend no more money on the venture, but made their information available to the U. S. Bureau of Mines, which conducted about 1000 ft. of diamond drilling on the property in the summer of 1944. This drilling was carried out principally in the vicinity of No. 3 tunnel, and outlines an ore body of limited horizontal extent, as indicated by the geophysical work. The general mass of the peridotite was shown to carry some sulphide mineralization, in two and three bands, but in only a small zone is the content of nickel and copper high enough to constitute ore, as shown on the plan map, Fig. 1. The Bureau of Mines estimated the ore zone to contain 30,000 tons with 0.6 to 1.7 per cent nickel and up to 0.7 per cent copper. No drilling

was done to test beneath the zone of peak electrical activity, to see whether or not the sulphides are heavier there. The drilling also left open the question of how far down the dip the ore body may be expected to extend. Geophysical methods do not give quantitative indications of the depth to the root of a sulphide body, but only a rough measure of whether it lies at depth, or close to the surface. The appearance of the profiles of electrical activity over this body would normally be taken to indicate a somewhat greater extension downdip than that shown by the outlines of the ore body traced by the Bureau of Mines. The possibility is therefore presented that the sulphides may extend further down the dip, under the quartz diorite roof. Whether it does or not is probably an academic question, because the drilling has indicated an ore body of too small a horizontal extent to be of commercial importance. The lack of any electrical activity in the hanging-wall side of the quartz diorite dike indicates no sulphide mineralization northeast of this intrusive; the geological data and the drilling suggest that the faulting, which probably preceded or accompanied this intrusion, had lifted the deeper extension of the ore body upward, and that this faulted section in the hanging wall of the dike has since been removed by erosion. The immediate area therefore lacks commercial interest.

Logical Order of Exploration

The work on this prospect clearly indicates the logical order in which to conduct an exploration program for the maximum efficiency and economy. Geophysical exploration methods are but one step in the progressive narrowing of the search for ore, and normally should occupy a position intermediate between the geological reconnaisance and the underground exploration by drilling, shaft or tunnel. In such an instance as the present one (ignoring for purposes of illustration the fact that the tunnels were driven 40 years ago), the discovery of the deposit should be followed by a geological reconnaisance to determine the approximate zone favorable for ore deposition. Following this, a geophysical survey would reveal the locations and relative importance of the sulphide deposits. The uninteresting ones, such as between profiles 5 + 00 and 9 + 50, could be eliminated at once (all the expense of tunneling here would be eliminated, as well as of test pitting in the barren areas) and attention concentrated on the better reactions between profiles 12 + 00 and 15 + 00. The only question to be answered would be whether the sulphides responsible for the stronger electrical reactions occur in quantity and values sufficient to constitute an ore body. A moderate amount of diamond drilling, with possibly some tunneling, would usually answer that question, if it is to be a negative answer, thereby saving much costly, and wasted, underground development. If the answer, on the other hand, is encouraging, the geophysical and preliminary drilling results can point the way for further exploration to reveal the significance of the ore occurrence.

Acknowledgments

Appreciation is hereby expressed to the U. S. Bureau of Mines, Dr. R. R. Sayres, Director, for supplying the drill-log data, and to the U. S. Geological Survey, Dr. W. P. Wrather, Director, for releasing maps of the surface geology and sections used in this article.

Effect of Dipping Strata on Determinations of Potential-drop Ratio

By Maynard H. Jameson,* Junior Member A.I.M.E.

(New York Meeting, February 1941)

Earlier investigations of the potential-drop-ratio method of electrical prospecting have indicated that under suitable conditions this method is well adapted to the location of formation boundaries in stratified ground. A description of this development was given several years ago by H. Lundberg and Th. Zuschlag.[1] The curves published by these authors for the potential-drop-ratio variation above a horizontal contact indicated a definite relation of the position of the curve peak to the depth of the interface.

The theory underlying this relation was subsequently studied by Z. Mitera in greater detail,[2] and the theoretical deductions were compared with the results of tank experiments.

The investigations available at this writing were confined to studies of horizontal formation boundaries. It is the purpose of this paper to extend the scope of the previous work to the problem of dipping layers.

Theory

Consider the case of three media of different resistivities, whose interfaces are not parallel. If a point-source is located in one of these interfaces, its images do not lie in a straight line, but on the circumference of a circle whose center is at the hypothetical junction of the interfaces.

R. F. Aldredge[3] determined the relation that exists between the degrees of dip of the two interfaces and the distances between the various images and the point for which the potential is to be found. As seen in Fig. 1, three media of resistivities ρ_0, ρ_1, and ρ_2 are involved, and the source I is located at the interface of the media (ρ_0) and (ρ_1). The perpendicular depth of the lower interface is h, θ is the dip, R is the distance between source I and potential point P, and r is the distance between the images and that point.

To distinguish between images lying above the ground interface and those below, the notation "odd" and "even" images will be employed; images below the ground interface will be termed "odd" and those above "even." The following relations govern the distances between either kind of images and the potential point:

Even Odd

$$r_0 = R$$
$$r_1 = [r_1] = [R^2 + 4h(h + R\sin\theta)]^{1/2}$$
$$r_2 = [r_2] = [R^2 + 4h(2\cos\theta)^2(h + R\sin\theta)]^{1/2}$$
$$r_3 = [r_3] = [R^2 + 4h(4\cos^2\theta - 1)^2 (h + R\sin\theta)]^{1/2}$$
$$r_4 = [r_4] = [R^2 + 4h(4\cos\theta\cos 2\theta)^2 (h + R\sin\theta)]^{1/2}$$
$$r_5 = [r_5] = [R^2 + 4h(4\cos^2\theta\cos 2\theta + \cos 4\theta)^2 (h + R\sin\theta)]^{1/2}$$
$$r_6 = [r_6] = \{R^2 + 4h[2\cos 3\theta(4\cos^2\theta - 1)]^2 (h + R\sin\theta)\}^{1/2}$$
$$r_n = [r_n] = \{R^2 + 4h[f(\cos\theta)]^2(h + R\sin\theta)\}^{1/2}$$

As previously pointed out, the images of the source are on the circumference of a circle. If the angle of dip is θ, the angle measured from the horizontal to the first image is 2θ; to the second image it is 4θ, and so on. Since the limit of the reflecting interface is at its outcrop, the last possible

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[1] References are at the end of the paper.

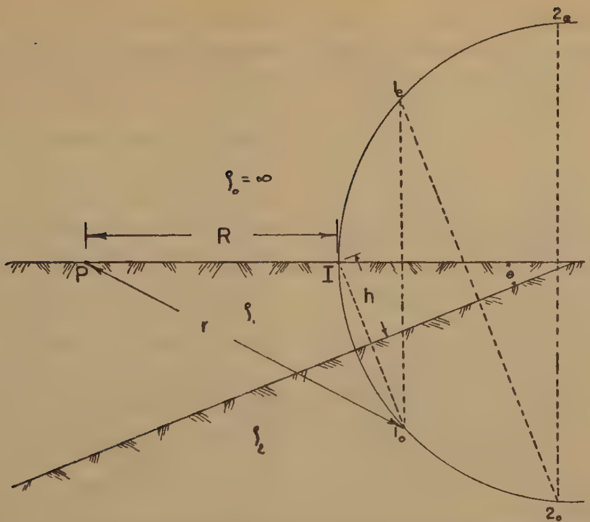

FIG. 1.—RELATION BETWEEN IMAGES AND DIP OF INTERFACES.

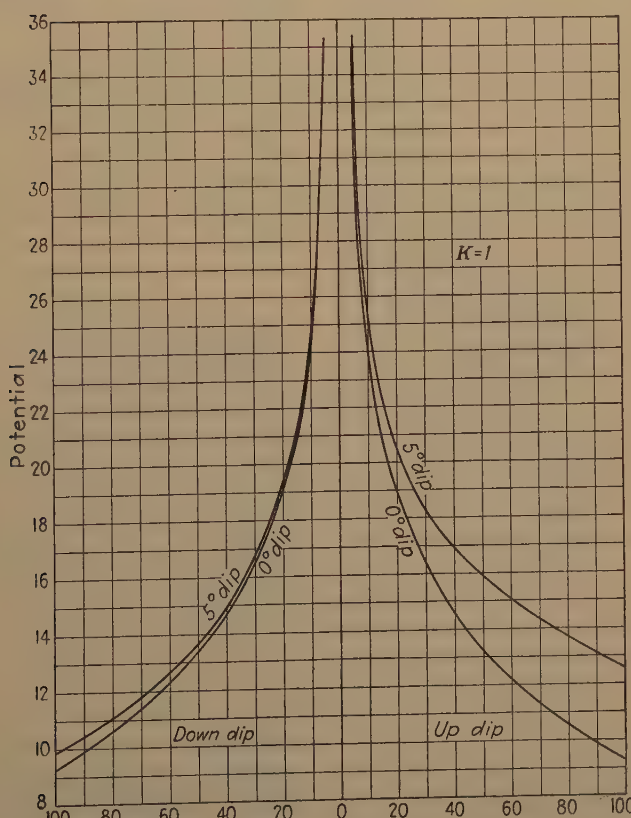

FIG. 2.—CURVES OF POTENTIAL DISTRIBUTION FOR ZERO AND 5° DIPS.

image is at an angle of 90° from the horizontal. Hence, $2\theta \times n$ cannot exceed 90°, so that the maximum number of odd images is $n_{max.} = \frac{\pi}{4\theta}$. The total number

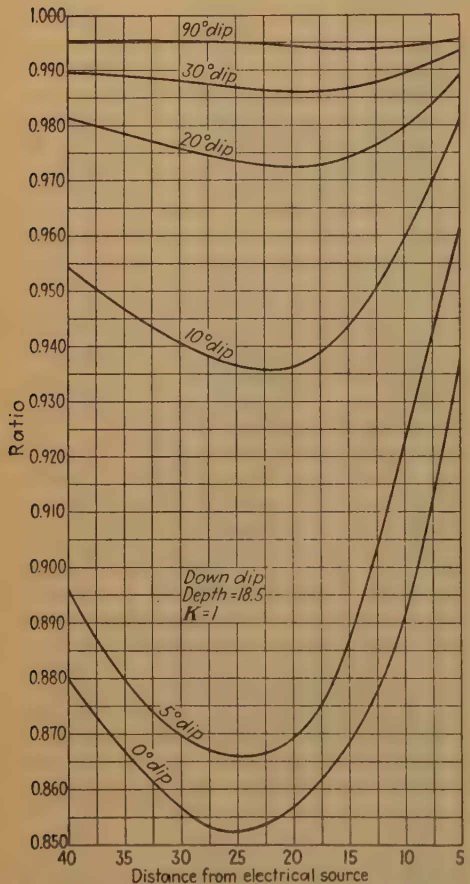

FIG. 3.—POTENTIAL-DROP RATIO FOR CONSTANT SPREAD.
Electrode interval, 5 distance units.

of images, odd and even, is twice this amount.

The potential at the point P due to the point source I and its images is then given by

$$V_p = \frac{\rho}{2\pi}\left[\frac{I_0}{r_0} + \frac{I_{1o} + I_{1e}}{r_1} + \frac{I_{2o} + I_{2e}}{r_2} + \cdots\right]$$

where r_1, r_2, etc. are the distances of the various images to the point P, I_0 is the intensity of the source, I_{no} is the intensity of the nth "odd" image, and I_{ne} is the intensity of nth "even" image.

The intensity of these images is a function of the reflection constant k, which is related to the resistivities of two media m and n, on either side of the interface, by the relation $k = \frac{\rho_m - \rho_n}{\rho_m + \rho_n}$. As applied to the upper interface, the reflection factor k_1 is 1, since the resistivity of the upper medium is infinite. The reflection constant for the lower interface is $k_2 = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$. Hence, the intensities of the images are:

ODD IMAGES	EVEN IMAGES
$I_1 = k_2 I$	$I_1 = k_2 k_1 I = k_2 I$
$I_2 = k_2 k_2 I = k_2^2 I$	$I_2 = k_2^2 k_1 I = k_2^2 I$
$I_n = k_2 k_2 \cdots I = k_2^n I$	$I_n = k_2 k_2 \cdots I = k_2^n I$

The intensities of the even and odd images are identical. Substituting these values in the general expression for the potential, we obtain

$$V_p = \frac{\rho I}{2\pi}\left[\frac{1}{r_0} + 2\left(\frac{k_2}{r_1} + \frac{k_2^2}{r_2} + \frac{k_2^3}{r_3} + \cdots \frac{k_2^n}{r_n}\right)\right]$$

CALCULATION

The application of this expression to an evaluation of potential-drop ratios involves three unique series and does not lend itself readily to simplification, therefore it is necessary to make the calculations in two steps: (1) calculation of the distances of the images, and (2) calculation of the potentials. From the potentials, the potential differences and the ratios of potential differences are readily obtained.

At the outset of the work it was thought possible to eliminate the first step by employing a graphical method. A large-scale drawing was made upon which it was possible to measure distances of images directly. Various control methods were used to give increased accuracy; but the

accuracy obtained was not sufficient, and the graphical method was abandoned.

In plotting curves based on measured distances, it was noted that the irregularities increased with an increase of distance. This, at first, appears contrary to expectation since an error in the measurement of a large distance would have less effect than in a shorter distance. The reason for the increase in error is that the potential drops decrease with an increase in distance; therefore greater accuracy is required for greater distances, and calculations were carried to the third decimal place of the arbitrary potential unit employed. The maximum accuracy attainable by the graphical method was one decimal place.

Calculations were simplified somewhat by choosing certain values of dip. The greatest symmetry and repetition of distances was attained by using dip angles of 0°, 5°, 10°, 20°, 30° and 90°; by calculating image distances for 5° dip, those for 10°, 20°, 30° and 90° dip are readily obtained. In order that a comparison may be made between curves obtained from various values of dip, it is desirable to maintain the perpendicular distance at a constant value. This is equivalent to a rotation of the interface about the point source.

The maximum inflection obtainable in potential-drop ratio curves results when k, the reflection constant, is equal to one. As the value of k decreases, the amplitude of the peaks becomes less. Since the principal objective of this paper was a determination of the position of the peaks, calculation was based on a value of k giving the maximum inflection. Curves for 0° dip were calculated on the basis of six images. For a dipping stratum, the total number of images is limited to $\frac{\pi}{2\theta}$, as stated before.

Two types of electrode spreads, constant and expanding, are considered in the following paragraphs. Potential drops obtained with the former become smaller as the distance from the source increases. Potential drops for expanding spreads, or for constant ratios of spread to electrode distance, tend to be less dependent on distance, since the potential drop between adjacent electrodes is considerably larger than that in the corresponding constant-spread arrangement.

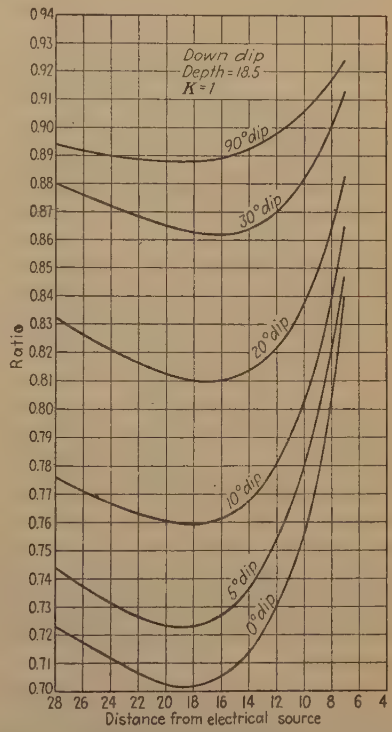

FIG. 4.—POTENTIAL-DROP RATIO FOR EXPANDING SYSTEM.
Electrode interval, ⅛ of center stake distance.

Calculated potential-drop ratios were corrected by the factor $\frac{R-b}{R+b}$, which reduces the ratio curve for homogeneous ground to a straight line. This correction may vary from zero to unity for electrodes at constant interval b; for an expanding system, the correction is a constant.

RESULTS

In Fig. 2, curves of potential distribution are illustrated for zero and 5° dips, so that the updip and downdip sides of the point source may be compared. The effect of dip

is less on the downdip side than on the updip side, owing to the "swinging under" of the images caused by the dip of the interface. When the potential of the images

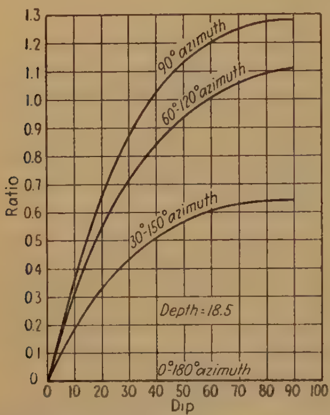

FIG. 5.—RATIO OF DISPLACEMENT AND PERPENDICULAR DISTANCE (CONSTANT SPREAD).

alone is considered, the point of maximum potential is not at the point source but some distance from it on the updip side; hence, a decided flattening of the resultant curve is observed. The converse of the above effect is produced on the downdip side.

From the potentials, the potential-drop-ratio curves have been calculated for profiles in the direction of maximum dip. If the profile is run in another direction, and if δ is the angle that this profile makes with the direction of strike, the displacement of the potential-drop-ratio peaks from the normal position of 0° dip is given by $D = d \sin \delta$, where D is the displacement in any azimuth and d is the maximum displacement (see also Figs. 5 and 6).

Fig. 3 gives potential-drop-ratio curves for a constant spread. The maximum amplitude ranges down to a ratio of 0.8525. Potential-drop-ratio curves for an expanding system (Fig. 4) range in amplitude to a maximum of 0.7025. Since the amplitude is measured from a reference ratio of unity as established for homogeneous ground, an expanding system gives maximum peak amplitude. On the other hand, the curves of the expanding system do not fall off as rapidly after the peak is reached,

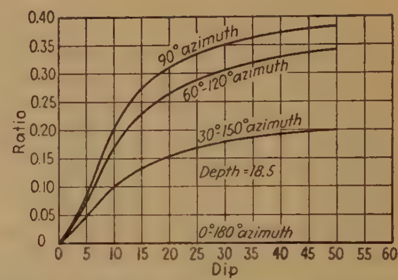

FIG. 6.—RATIO OF DISPLACEMENT AND PERPENDICULAR DISTANCE (EXPANDING SPREAD).

as do those of the constant-spread system. The displacement of the peaks is generally toward the origin.

To enable a comparison between the amount of displacement and dip, the ratio of displacement and perpendicular distance is plotted on Figs. 5 and 6, which show that dip is more effective in the constant-spread system than in the expanding system.

From the relation previously developed between effective dip and displacement, curves showing the change of displacement with azimuth have been incorporated in Figs. 5 and 6.

ACKNOWLEDGMENT

The writer wishes to acknowledge the advice and assistance of Dr. C. A. Heiland, Head of the Department of Geophysics, Colorado School of Mines, under whose supervision this work was conducted, and of Mr. R. F. Aldredge, whose preliminary work formed the basis for the investigation reported in this paper.

REFERENCES

1. H. Lundberg and T. Zuschlag: *Trans.* A.I.M.E. (1932) 97, 47–62.
2. Z. Mitera: Colorado School of Mines *Quarterly* (1937) 32, (1), 189–221.
3. R. F. Aldredge: Effect of Dipping Strata on Earth Resistivity Determinations. Colorado School of Mines *Quarterly* (1937) 32 (1), 169–186.

DISCUSSION

(*J. J. Jakosky presiding*)

MEMBER.—How is it you always work on the opposite side from your remote stake, never between the two stakes?

C. A. HEILAND.*—That complicates matters. As it is, conditions as treated in Jameson's paper are complicated enough.

MEMBER.—Is not your field more uniform on the side away from the remote current state?

C. A. HEILAND.—Two electrodes must be considered, two primary electrodes. If you can consider one primary electrode in infinity, it makes no difference on which side of the other electrode you work.

MEMBER.—But you never get an infinity.

C. A. HEILAND.—That all depends on how far you are away from the other electrode. If the distance between the primary electrodes is five to eight times the distance between the secondary electrodes and the near primary electrode, the second primary electrode is in infinity to all intents and purposes. This is readily explained as follows: Take two electrodes and draw a circle, with the base length as radius, about the far electrode and through the near electrode. This circle is then an isopotential line about the far electrode; therefore the effect of the far electrode may be completely eliminated by making the P.D.R. observations along this circle. Now this is impracticable in the field, and the potential profiles are run at right angles to the base through the near electrode; that is, on a line tangent to the circle. This line approaches the circle more closely the greater the radius of the isopotential line; that is, the greater the distance between the primray electrodes. Experience has shown that a distance of five or eight times that between near electrode and middle potential stake puts the second primary electrode in infinity, so to speak.

* Heiland Research Corporation, Denver Colo., and Professor of Geophysics, Colorado School of Mines, Golden, Colo. Dr. Heiland presented Mr. Jameson's paper.

S. F. KELLY.*—As I understand it, you said that the line should be oriented so that it moves out to strike the underlying dipping surface—when it runs along right angles to the dip.

C. A. HEILAND.—With fixed spacings, you lose your dipping stratum eventually, because the depths become greater and greater, particularly at high angles of dip.

* Sherwin F. Kelly Geophysical Services, Inc., Wilmington, Del.; Geophysical Explorations Ltd., Toronto, Ont., Canada.

Further Advances in Prospecting by Electric Transients

By Gifford E. White*

(New York Meeting, February 1941)

Explanations of the basic procedure for making earth-conductivity studies by the Eltran method have already appeared in several places.[1,2,3] In its essentials, this method consists of applying step functions of voltage to one pair of earth grounds and measuring the transient potential resulting at a separate pair of ground points. As previously pointed out,[4] the transient potential resulting from a suddenly applied steady voltage is the indicial transfer function of Carson,[5] which has been extensively studied in network theory.

The discussion here, with one special exception, will ignore the problem of how the physical configuration of the earth affects the transient response voltage; it appears that this phase of the problem has been solved in only a few special cases having any direct bearing on the prospecting problem.

Entirely distinct from the potential-theory aspect of the conductivity problem is the interesting material that can be had from studying the well-known network relations between cause and effect in linear circuits, and thus deducing criteria for the application of the several experimental methods available. To do this, only one assumption need be made about the nature of the earth. The earth is to be considered a linear conductor within the tolerance of ordinary measurements.

The discussion will be restricted to collinear electrode configuration like that of Fig. 1, since this is the only type of spread practical for use with driving currents that vary with time. Here one pair of grounds carries the driving current, and in line with these and external to them is a pair of potential probes. The problem will be to consider the relation between the different voltages appearing between the potential circuit terminals when various types of driving voltage sources are inserted in the current circuit.

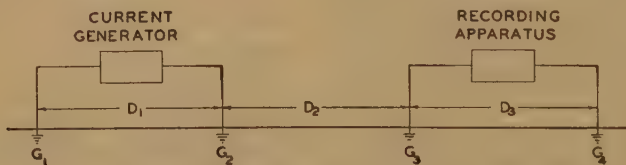

Fig. 1.—Diagram of field setup.

Suppose that the grounding points G_1 and G_2 make good contact with the earth, and that a battery of sufficient voltage to produce one ampere of direct current is introduced into the current circuit by the closing of a switch. The potential transient response to such a voltage can be measured by taking an oscillogram at the potential circuit terminals, giving the time function that has been called $A(t)$.[4] This time function has been solved for analytically in the case of a homogeneous earth,[6,7] and the

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[1] References are at the end of the paper.

results can be used to make some estimate of the behavior of $A(t)$ under other simple conditions.

Of particular interest for some of the later discussion is the value that $A(t)$ takes on just after the closing of the switch on a battery in the current circuit. Using Riordan's equation 3,[7] and converting it to our particular case and notation, we get for a homogeneous earth of resistivity ρ,

$$A(t) = \frac{\rho}{2\pi}\left[-\frac{\zeta(D_2)}{D_2} + \frac{\zeta(D_1 + D_2)}{D_1 + D_2} + \frac{\zeta(D_2 + D_3)}{D_2 + D_3} - \frac{\zeta(D_1 + D_2 + D_3)}{D_1 + D_2 + D_3}\right] \quad [1]$$

where

$$\zeta(u) = -1 + \left(\frac{1}{2} + \frac{\pi u^2}{\rho t}\right) erf\, u \sqrt{\frac{\pi}{\rho t}} + \frac{u}{\sqrt{\rho t}} exp\left(-\frac{\pi u^2}{\rho t}\right)$$

For large values of the argument, corresponding to small values of time,

$$\zeta(u) = \left[-\frac{1}{2} + \frac{\pi u^2}{\rho t}\right]$$

Inserting this in Eq. 1 gives, as t approaches 0,

$$A(0) = \frac{\rho}{2\pi}\frac{1}{2}\left[\frac{1}{D_2} - \frac{1}{D_1 + D_2} - \frac{1}{D_2 + D_3} + \frac{1}{D_1 + D_2 + D_3}\right] \quad [2]$$

This can be recognized as the ordinary formula for the direct-current voltage transfer of the given electrode spread,[9] except that Eq. 2 gives only half the direct-current value. Then, in a homogeneous earth, the initial value of the indicial response of the earth is one-half the final steady-state value, regardless of the spacing of the collinear electrode spread.

In Fig. 2*a* are shown the essential features of $A(t)$ for a homogeneous earth. The transient jumps to one-half its final value, starts from this with zero slope, and builds up to its final height in a manner that depends upon the resistivity and the electrode spread. Data to give the whole of $A(t)$ for the homogeneous earth are given by Riordan.[7]

Suppose that the earth is no longer homogeneous. Just after the closing of the switch in the battery circuit, current will begin flowing in the earth, but because of the restrictions usually lumped together as skin effect, virtually all the current flow is confined to the surface layer. This means that the height of the discontinuity, $A(0)$, at $t = 0$ depends upon the value of the shallow resistivity alone, while the shape of the remainder of the transient must of course depend upon the constants of the deeper layers of the earth. If the surface of the earth is of relatively high-resistivity material, $A(0)$ is greater than half the final height of the transient, as in Fig. 2*b*. If the surface layer has a relatively low resistivity, $A(0)$ may be small, as in Fig. 2*c*.

Until now, the voltage in the current circuit has been spoken of as the step-function driving force. It is much more convenient to make computations in terms of current, so experimental oscillograms have been taken to see whether the current produced by a suddenly applied constant voltage is also a step function. It appears that because of the short current-carrying conductors in use (seldom over 2000 ft. long), the current takes on its final value in a time negligible on the time scale usual for these transient measurements. This is equivalent to saying that the current grounds and the current-carrying conductor together have a constant resistive impedance over the frequency range that is expected to be used. Hence, the current will be considered the primary driving force, and will be taken as a replica of the driving-voltage wave shape. $A(t)$ will be the transient voltage from one ampere of direct current applied as a step function of this sort.

If a current of any other wave shape were to be introduced into the earth at the current grounds, the voltage produced at the potential probes would be given by the superposition-theorem integral equation[8]

$$e(t) = A(0)i(t) + \int_0^t A'(\lambda)i(t-\lambda)d\lambda \quad [3]$$

$i(t)$ is any new driving current, perfectly arbitrary within the range of the assumptions just made, and $e(t)$ is the resultant voltage produced in the potential circuit. $A'(t)$, the time derivative of $A(t)$, has already been discussed, and its relation as the response to a perfect surge has been given.[4]

In a recent modification of the Eltran method, the battery voltage has been replaced by a charged condenser, suddenly applied to the current circuit and allowed to discharge. The current into the ground varies approximately exponentially, as has been verified by oscillograms. If E is the charging voltage of the condenser of capacity C, and R is the effective resistance of the current circuit, the current driving surge is

$$i(t) = E/R \, exp \, (-t/RC)$$

Insert this into Eq. 3 and obtain

$$e(t) = A(0)\frac{E}{R} exp \, (-t/RC)$$
$$+ \int_0^t A'(\lambda)\frac{E}{R} exp \, [-(t-\lambda)/RC]d\lambda \quad [4]$$

Solve for $A'(t)$ by the methods of integral equations and find

$$A'(t) = \frac{R}{E}e'(t) + \frac{1}{CE}e(t) \quad [5]$$

These will be the basic equations by which the computation of Eltran surge transient records will be explained.

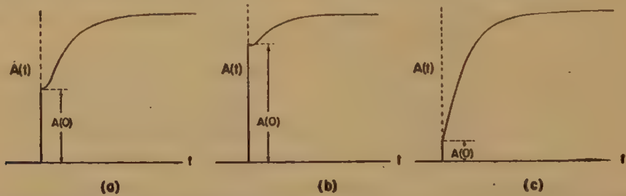

FIG. 2.—STEP-FUNCTION TRANSIENTS IN EARTHS OF VARYING SURFACE RESISTIVITIES.

Block diagrams of the apparatus employed at present in making the Eltran surge transient records are shown in Figs. 3 and 4, and are self-explanatory for the most part. The surge generator is a 3000-volt condenser with a maximum capacity of 145 microfarads, charged from a rectifier of low power and high voltage, and discharged into the earth through a special mercury-vapor control tube capable of passing the 200 or 300 amp. of peak current in the surge. A short time before the discharge of the condenser into the current grounds, a synchronizing impulse is transmitted by radio to the observer's truck, which contains the recording apparatus. With the low-frequency amplifier and

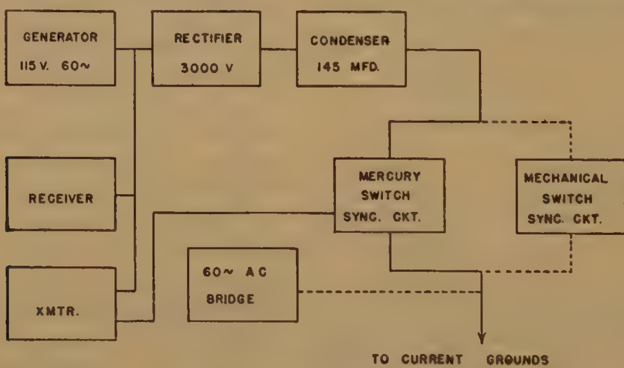

FIG. 3.—SURGE GENERATOR.

cathode-ray oscillograph and its camera are several specialized circuits, some of which will be described. The recording problems are quite unusual, hence much of the apparatus is unconventional in nature.

Solving for $A(0)$ gives

$$A(0) = e(0)R/E \qquad [6]$$

Hence, knowing the effective total resistance of the current circuit and the

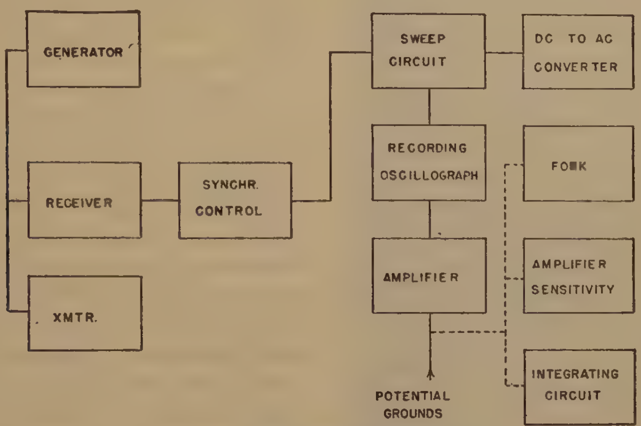

FIG. 4.—RECORDING APPARATUS.

voltage to which the condenser was charged, the amount of the initial jump in the response to a step of current can be

The electronic switch discharges the surge into a ground circuit with a total resistance of 10 or 15 ohms. The total resistance is taken as the value from a Wheatstone bridge at 60 cycles, and is measured at every setup. This is the resistance R in Eqs. 5 and 6, and is important because it determines the rate of decay of the surge. The time constant of the current circuit is usually of the order of 0.001 sec., hence the current surge contains frequency components of high amplitude well beyond the high audiofrequencies.

Applying the current surge to the grounds, the potential transient is recorded by photographing the cathode-ray oscillograph screen, and later making a print like that shown in Fig. 5. This oscillogram is the function $e(t)$, which appears in Eqs. 4 and 5. The first feature that appears on the oscillogram is the discontinuity at the time of application of the surge. The significance of this discontinuity can be seen by placing $t = 0$ in Eq. 4, obtaining

$$e(0) = A(0)E/R$$

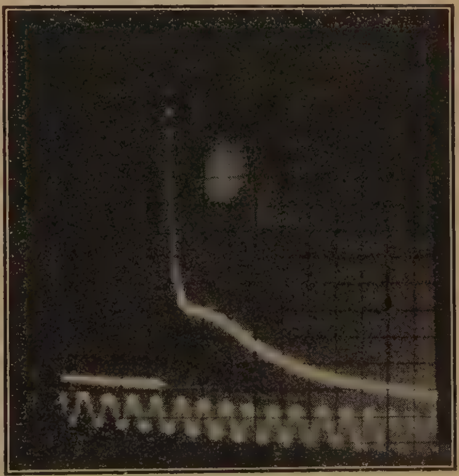

FIG. 5.—VOLTAGE TRANSIENT OSCILLOGRAM, $e(t)$.

found from $e(t)$, the surge response. This raises the possibility of using $A(0)$ to assign a value to the surface resistivity, since it appears that $A(0)$ must depend upon the shallow resistivity alone.

Since $A(t)$ is produced by one ampere of steady current, its magnitude for large values of time must be the voltage to current ratio of direct-current prospecting.

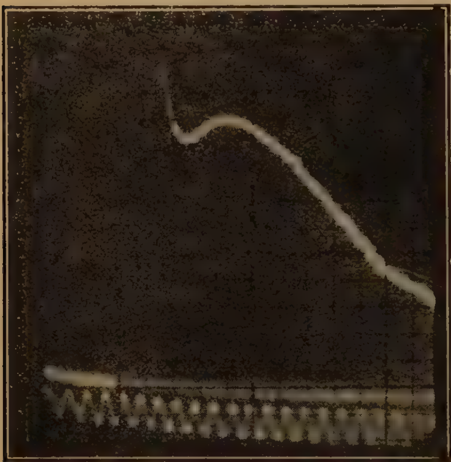

FIG. 6.—ENLARGED PORTION OF $e(t)$.

This final value of $A(t)$ is commonly called the mutual resistance, and from it is calculated the common apparent resistivity by

$$A(\infty) = mr = \frac{\rho}{2\pi} f(D) \qquad [7]$$

$f(D)$ depends upon the spread geometry and for Fig. 1 is given by

$$f(D) = \left[\frac{1}{D_2} - \frac{1}{D_1 + D_2} - \frac{1}{D_2 + D_3} + \frac{1}{D_1 + D_2 + D_3}\right]$$

Suppose that instead of using the mutual resistance in Eq. 2, we insert $A(0)$, which is equivalent to using $2A(0)$ in place of $A(\infty)$ in Eq. 7, and solve for the resistivity:

$$\rho = 2\pi 2A(0) \frac{1}{f(D)} \qquad [8]$$

The resistivity given by Eq. 8 must be the surface resistivity if the top layer is uniform, since at the time $A(0)$ is taken only the currents at the surface are contributing to the transient voltage. As long as this uniform surface layer is not of negligible thickness nor of infinite resistivity, the quantity given by Eq. 8 will be independent of the deeper layers.

A question that arises is the significance of the value obtained for the resistivity by using $A(0)$ when the surface layer is not uniform. Just after closing the switch to apply the surge to the current grounds, an electromagnetic field is set up over all the surface near the wire spread. The manner in which the surface currents begin to flow is determined by the resistivities in the neighborhood, and the voltage first indicated in the potential circuit must then be determined by an averaging of all the different surface effects. This might easily be an experimental advantage, since a value for ρ found by using a large electrode spread will be the same as an average for a large number of readings that might be taken by short-spread direct-current methods. The resistivity determined from $A(0)$ in a large spread must be independent of small local variations.

The size of the discontinuity $A(0)$ is called H_1 by the field computers, and usually plotted directly in millivolts per ampere without conversion into actual resistivity units.

Further inspection of the potential transient produced by the current surge will show that, following the initial discontinuity, a smooth maximum occurs in the oscillograph trace. The significance of this maximum appears when we consider that the oscillogram of the surge transient is approximately the time derivative of the transient due to a step of direct current. $A(t)$ as it is sketched in Fig. 2 shows that one point of maximum slope should be expected somewhere on the shoulder of the curve. Eq. 5 allows us to solve for this derivative function, $A'(t)$, from the surge oscillogram $e(t)$. At the time of taking $e(t)$ in the field, the photograph is provided with a time scale from a 400-cycle tuning fork, and the sensitivity of the amplifier is measured in millivolts per inch. With these

data for coordinate scales, $e(t)$ can be measured from the print and inserted in Eq. 5, and the solution made for $A'(t)$. $e'(t)$ is found graphically by estimating the slope of the tangent line at the value of t for which $A'(t)$ is desired, and $A'(t)$ is thus point-plotted. In practice, the term involving $e'(t)$ is kept as small as possible by making R/E small in the field, reducing the importance of any errors that might enter into estimation of the slope of $e(t)$. A quick field routine has been devised for the use of the field computers in evaluating Eq. 5.

One quantity of particular interest is the maximum of $A'(t)$, the maximum slope of $A(t)$. This quantity is referred to as H_2 in the computations, and is found by taking ordinates of $e(t)$ near the oscillogram maximum and inserting them in Eq. 5 until the maximum height of $A'(t)$ is found. To assist in this, an oscillogram showing only a part of the transient near the maximum is made at each station, as shown in Fig. 6. The dimensions of $A'(t)$ are commonly given in millivolts per coulomb.

This maximum, H_2, of the perfect surge potential transient $A'(t)$ has no easily ascertainable relation to the geometrical configuration of the earth, but it provides a quickly obtainable index to the general nature of the transient response. Some other feature of the transient might be picked, which would have as much significance, but this maximum height can be found with more accuracy and rapidity than any of the other possible parameters.

The ordinate at the first part of the transient $e(0)$, compared with the height of the smooth maximum that follows, is of interest. These two amplitudes are somewhat independent, since they do not change in the same way with changes in spread geometry, resistivity, or the shape of the current surge. In fact, in the first surge transient work[4] the current grounds were separated from the potential probes by 8000 ft., and $e(0)$ was so small that it was overlooked. Under conditions commonly encountered in the Gulf Coast area, the discontinuity $e(0)$ may vary from $1/10$ to 100 times the height of the oscillogram second maximum.

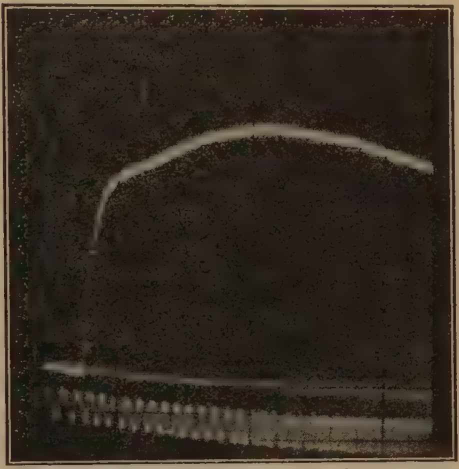

FIG. 7.—INTEGRAL OF $e(t)$.

It might be pointed out that the method of using current steps from a battery to study $A(t)$ itself would in general be an unsatisfactory method of computing $A(0)$, because of the difficulty in separating the discontinuity from the steeply sloping transient. The current surge accentuates the discontinuity on the oscillogram.

Integration of Eq. 5 with respect to time leads to the interesting relation:

$$A(t) = \frac{R}{E} e(t) + \frac{1}{CE} \int_0^t e(\lambda)\, d\lambda \qquad [9]$$

By taking t large, Eq. 9 reduces to

$$A(\infty) = \frac{1}{CE} \int_0^\infty e(t)\, dt \qquad [10]$$

The first term on the right-hand side of Eq. 9 must become 0 because $e(t)$ goes to 0 for large values of t.

Eq. 10 says that if the integral of the potential due to the current surge is taken by any suitable method, and the integral divided by the total charge of the current surge, the conventional mutual resistance

of direct-current prospecting is the result. This integral can be taken by a planimeter from the field oscillogram, but a direct electrical integration proves to be more accurate, and quicker.

This mutual resistance, which is the same as $A(\infty)$, can be inserted in Eq. 7 to give the conventional direct-current apparent resistivity of the earth. However, the mutual resistance is often left as millivolts

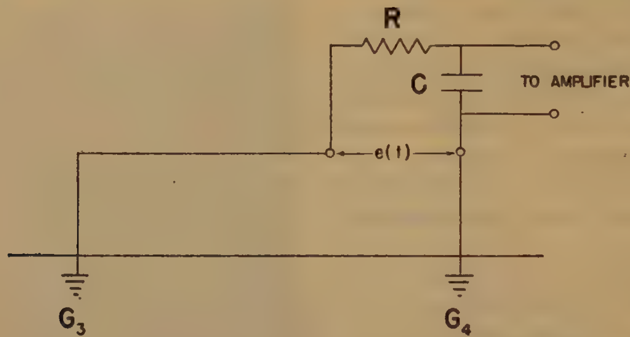

FIG. 8.—INTEGRATING CIRCUIT FOR MUTUAL RESISTANCE.

per ampere because all the stations on each prospect are taken with the same electrode spacing.

If the potential transient from the earth is fed directly into an integrating network like that in Fig. 8, the output from the network can be made to approximate the integral of $e(t)$ as closely as we please by choosing the product of RC large enough. The duration of $e(t)$ is less than a second, therefore it is practical to make the circuit sluggish enough so that the maximum of the slow voltage transient across the output can be taken as the integral of $e(t)$. When the current surge is applied to the ground, the voltage across the integrating network is photographed in the usual way, as shown in Fig. 7, and the maximum height is later read by the computer. The action of this circuit is much like that of a ballistic galvanometer, in which the maximum throw is taken as the desired integral.

If this maximum output M of the integrating network is measured in millivolts, and Q is the charge in the current surge in coulombs, the mutual resistance is given by

$$mr = \frac{MRC}{Q} \text{ millivolts per ampere} \qquad [11]$$

assuming that RC is large. R and C here refer to the integrating network of Fig. 8, and not to the surge generator circuit in which the same symbols appear.

In Fig. 9 is a plot of the three quantities H_1, H_2, and mr, taken at 1000-ft. intervals along a straight line, using a spread in which $D_1 = 2000$ ft., $D_2 = 2000$ ft., and $D_3 = 1000$ ft. The profile is across an undrilled prospect in the Gulf Coast. It will be noted that the surface resistivity is different from the average deeper resistivity given by the mutual resistance (mr), and the two have opposite trends. This is not necessarily significant, but illustrates their independence. The transient maximum H_2 resembles neither in this profile; since it implicitly involves a different type of resistivity averaging from the other two quantities, it may well be independent in trend also.

From the fact that the step-function response of the earth, $A(t)$, has a discontinuity at $t = 0$, it can be inferred that high-frequency voltages are transferred from the current circuit to the potential measuring circuit. In fact, if current of increasingly higher frequency were to be inserted into the current circuit, the voltage transfer would approach a fixed value determined by $A(0)$. Yet the attenua-

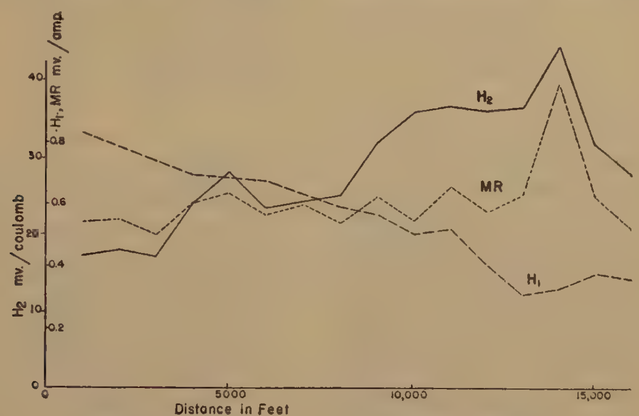

FIG. 9.—DATA ON A TYPICAL ELTRAN PROFILE.

tion of currents in a conductor like the earth must increase with frequency. The explanation is that the high-frequency currents produce fields that are guided along the surface of the earth, much as along a transmission line. The effective penetration of the electromagnetic field at the higher frequencies must be quite small, as has been estimated by a number of different investigators.[10,11] However, the value of the surface resistivity determines the amount of high-frequency transmission, as can be shown by a quite general approach to the problem of a field about a current-carrying conductor.[12] Since the high-frequency transmission and A(o) are mutually dependent, the computation of the surface resistivity from A(o) is justified.

Because the surge transient oscillograms exhibit a discontinuity at the origin and a later maximum, it might be inquired whether other maxima are not possible. The extreme view of this is the expectancy that if a sufficiently sharp current surge is inserted into the earth the voltage oscillogram will exhibit the characteristics of a reflected wave. Such phenomena would presume the possibility that the earth is a medium capable of transmitting electromagnetic waves of the nature of those possible in dielectric media. Maxwell's equations[10] show that as long as the earth is considered even a reasonably good conductor, wave propagation can take place only at absurdly high frequencies, such as the shortest radio waves. At these frequencies, unless the earth can be shown to exhibit an anomalously low conductivity, the effective penetration of moist earth in any engineering sense is a matter of feet instead of the hundreds of feet required in electrical prospecting. At high frequencies, energy may travel along wire conductors at the surface and along the surface of the earth itself, but not into the earth to any useful depth.

The low-frequency currents spread through the earth in a diffusion process in which the attenuation increases at a rapid rate with frequency, so that the potential transient from the earth-conductivity effect is a smooth and distorted representation of the current surge. If the current surge has only one peak, only one maximum can be expected in the earth-conduction contribution to the potential transient.

It often happens that if a station setup is made near grounded conductors such as telephone and power lines, complex potential transients may result, which resemble reflection phenomena. The currents induced into paralleling surface conductors may produce fairly high potential circuit volt-

ages which exhibit numerous oscillations near the initial portion of the transient. Out of the thousands of field oscillograms taken under widely varying conditions, never more than one true maximum has been found on a surge transient except under such conditions as these.

The time from the application of the surge out to the maximum point of the surge potential transient has been measured on a large number of stations, to see whether it offered promise of useful data. In no sense can the time out to the peak of the transient be considered a time of transit such as exists in wave phenomena like mechanical waves. The events taking place in the electrical transient are more like those of a heat-flow transient, and the maximum value represents the amount of maximum energy diffusion rather than the passage of a wave. The maximum is broad enough so that the time from the origin is not sufficiently definite to be measured accurately. So far this elapsed time has not been proved to have any practical significance.

Acknowledgments

The author wishes to express his warmest thanks to Dr. L. W. Blau, of the Humble Oil and Refining Co., who encouraged and supported this experimental work, and to the Humble Eltran party for cooperation in obtaining the field data.

References

1. L. Statham: Electric Transients in Electric Prospecting. *Geophysics* (June 1936) **1**, 2.
2. L. W. Blau: U. S. Patent No. 1911137.
3. S. S. West: Electrical Prospecting with Non-Sinusoidal Currents. *Geophysics* (Oct. 1938) **3**, 4.
4. G. E. White: Application of Rapid Current Surges to Electric Transient Prospecting. *Trans.* A.I.M.E. (1940) **138**, 441.
5. J. R. Carson: Transient Oscillations. *Trans.* Amer. Inst. Elec. Engrs. (1919) **38**, 345.
6. R. M. Foster: Mutual Impedance of Grounded Wires. Bell Syst. *Tech. Jnl.* (July 1931) **10**, 408.
7. J. Riordan: Transients in Grounded Wires Lying on the Earth's Surface. Bell Syst. *Tech. Jnl.* (July 1931) **10**, 420.
8. V. Bush: Operational Circuit Analysis. New York, 1932. John Wiley and Sons.
9. F. Wenner: A Method of Measuring Earth Resistivity. Nat. Bur. Stds. *Sci. Paper* **258** (1915).
10. A. S. Eve: Absorption of Electromagnetic Induction and Radiation by Rocks. *Trans.* A.I.M.E. (1932) **97**, 160. Geophys. Prospecting.
11. Peters and Bardeen: Electromagnetic Methods. *Physics* (March 1932) **2**, 103.
12. K. A. Norton: The Propagation of Radio Waves over the Surface of the Earth and in the Upper Atmosphere. *Proc.* Inst. Radio Engrs. (Sept. 1937) **25**(9), 1203.

A Study of the Problem of Depth Determination by Means of Earth-resistivity Measurements

By William A. Longacre,* Member A.I.M.E.

(New York Meeting, February 1941)

In a previous paper[1] the author discussed the problem described by the title of this paper, outlining and reviewing the Gish-Rooney method, with comparison and brief analysis of the interpretation techniques of Roman[2] and Tagg.[3] Some aspects of the simple type of two-layer system were reviewed from various sources.[4,5,6]

The Two-layer Problem

For the configuration shown in Fig. 1, and for any electrode separation A, the

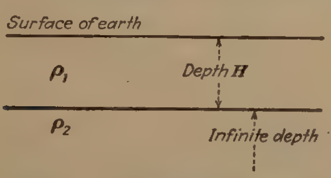

Fig. 1.—Two-layer system.

apparent resistivity is a function of the relative depth $\frac{H}{A}$, the overburden resistivity ρ_1, and a factor K defined by the equation

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \qquad [1]$$

where ρ_2 is the resistivity of the lower bed. Thus, by the known theory of electrical images,

$$\rho = \rho_1\left[1 + 2f\left(K, \frac{H}{A}\right)\right] \qquad [2]$$

where

$$f\left(K, \frac{H}{A}\right) = \sum_{n=1}^{n=\infty} K^n \left[\frac{2}{\sqrt{1 + 4n^2\left(\frac{H}{A}\right)^2}} - \frac{1}{\sqrt{1 + n^2\left(\frac{H}{A}\right)^2}}\right] \qquad [3]$$

The Multilayer Problem

As the number of isotropic, homogeneous, horizontal layers increases, the difficulties of interpretation multiply. The theory becomes much more involved, and in view of the state of our knowledge, the general problem is virtually impossible of exact solution. However, certain types of multilayer problems can be worked out in terms of two-layer theory.

Hummel,[7] Pirson,[8] Tagg,[3] Watson,[9] and others have pointed out the possibility of building up approximations of multilayer resistivity curves with suitable combinations of two-layer curves. Many three-layer curves can be constructed in this way to a good degree of accuracy, and special types of four-layer curves can be approximated. It is very likely that as the number of layers increases, the method of combination will not give good approximations except in very special cases. In the analysis of actual field data, the author has found that many obviously multilayer curves can be solved partially with a good degree of accuracy, using the theory that thin adjacent beds may be considered as one layer or zone, and applying two-layer theory to the extremities of the field curve.

Modified Tagg Method of Interpretation

Tagg's second method, though superior to his first, necessitates a large number

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1 References are at the end of the paper.

of master curves and a lengthy analysis of each set of field data. The large number of H, K curves will sometimes lead to so many intersections, over such a large area, that a statistical approach is necessary. Such a widespread set of intersections obviously indicates that the geologic conditions are not those assumed in the theory, or that the field data are slightly inaccurate, or both. The second cause of error can be greatly reduced, of course, and with carefully taken data the author has solved, at least partly, field curves that had failed to respond to other methods of analysis.

In an attempt to improve on Tagg's second method the following approach was developed:

In Fig. 2, A represents any electrode separation with related separations $1.2A$, $1.4A$, $1.6A$, $1.8A$, and $2.0A$. The corresponding apparent resistivities are represented by ρ_A, $\rho_{1.2A}$, $\rho_{1.4A}$, $\rho_{1.6A}$, $\rho_{1.8A}$ and $\rho_{2.0A}$. Thus from Eq. 2,

TABLE 1.—*Data for Master Curves, Conducting Bed*

H/A \ K	−0.1	−0.2	−0.3	−0.4	−0.5	−0.6	−0.7	−0.8	−0.9	−1.0
0.400	0.2072	0.2150	0.2239	0.2343	0.2472	0.2644	0.2899	0.3340	0.4370	1.0356
0.500	0.2088	0.2187	0.2302	0.2439	0.2611	0.2840	0.3166	0.3689	0.4696	0.7577
0.600	0.2096	0.2206	0.2333	0.2485	0.2672	0.2912	0.3239	0.3716	0.4493	0.6016
0.667	0.2099	0.2210	0.2340	0.2492	0.2677	0.2910	0.3214	0.3634	0.4262	0.5314
0.800	0.2097	0.2206	0.2330	0.2472	0.2638	0.2838	0.3083	0.3393	0.3801	0.4366
0.900	0.2093	0.2195	0.2310	0.2439	0.2587	0.2758	0.2962	0.3206	0.3508	0.3892
1.000	0.2087	0.2182	0.2286	0.2401	0.2531	0.2677	0.2846	0.3042	0.3270	0.3564
1.100	0.2080	0.2166	0.2260	0.2362	0.2474	0.2599	0.2739	0.2895	0.3074	0.3284
1.250	0.2070	0.2144	0.2224	0.2308	0.2399	0.2497	0.2605	0.2720	0.2848	0.2989
1.333	0.2065	0.2132	0.2204	0.2280	0.2361	0.2447	0.2538	0.2639	0.2747	0.2864
1.500	0.2055	0.2112	0.2168	0.2232	0.2296	0.2364	0.2435	0.2510	0.2589	0.2672
1.667	0.2046	0.2094	0.2143	0.2194	0.2246	0.2300	0.2356	0.2414	0.2474	0.2537
1.800	0.2041	0.2081	0.2124	0.2167	0.2216	0.2256	0.2302	0.2350	0.2399	0.2450
2.000	0.2033	0.2067	0.2101	0.2136	0.2171	0.2206	0.2242	0.2279	0.2316	0.2355
2.250	0.2026	0.2052	0.2079	0.2105	0.2131	0.2158	0.2185	0.2210	0.2239	0.2267
2.500	0.2021	0.2042	0.2063	0.2084	0.2105	0.2126	0.2147	0.2167	0.2188	0.2210
2.857	0.2015	0.2030	0.2045	0.2060	0.2074	0.2089	0.2104	0.2119	0.2133	0.2148
3.000	0.2014	0.2027	0.2040	0.2054	0.2066	0.2079	0.2093	0.2105	0.2118	0.2131
3.333	0.2011	0.2021	0.2032	0.2042	0.2052	0.2062	0.2072	0.2082	0.2092	0.2102
3.750	0.2008	0.2015	0.2023	0.2030	0.2038	0.2045	0.2052	0.2059	0.2066	0.2073
4.000	0.2006	0.2013	0.2019	0.2025	0.2031	0.2037	0.2043	0.2049	0.2055	0.2060

TABLE 2.—*Data for Master Curves, Insulating Bed*

H/A \ K	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.400	0.1932	0.1867	0.1802	0.1737	0.1671	0.1603	0.1531	0.1452	0.1364	0.1251
0.500	0.1919	0.1845	0.1774	0.1706	0.1638	0.1570	0.1501	0.1429	0.1349	0.1253
0.600	0.1913	0.1833	0.1759	0.1688	0.1620	0.1553	0.1486	0.1418	0.1345	0.1260
0.667	0.1911	0.1830	0.1754	0.1683	0.1615	0.1549	0.1483	0.1416	0.1347	0.1267
0.800	0.1912	0.1831	0.1756	0.1685	0.1618	0.1553	0.1490	0.1427	0.1361	0.1289
0.900	0.1915	0.1837	0.1763	0.1695	0.1629	0.1566	0.1504	0.1443	0.1380	0.1311
1.000	0.1920	0.1845	0.1775	0.1708	0.1645	0.1583	0.1523	0.1464	0.1404	0.1338
1.100	0.1925	0.1855	0.1787	0.1725	0.1664	0.1605	0.1547	0.1490	0.1433	0.1369
1.250	0.1934	0.1870	0.1810	0.1751	0.1695	0.1640	0.1586	0.1532	0.1477	0.1419
1.333	0.1938	0.1879	0.1822	0.1767	0.1714	0.1662	0.1610	0.1559	0.1506	0.1450
1.500	0.1947	0.1896	0.1846	0.1797	0.1749	0.1702	0.1655	0.1608	0.1560	0.1508
1.667	0.1954	0.1910	0.1866	0.1823	0.1781	0.1738	0.1696	0.1653	0.1609	0.1562
1.800	0.1960	0.1921	0.1882	0.1844	0.1806	0.1767	0.1729	0.1690	0.1649	0.1606
2.000	0.1967	0.1934	0.1901	0.1868	0.1836	0.1803	0.1769	0.1735	0.1700	0.1661
2.250	0.1974	0.1948	0.1922	0.1895	0.1869	0.1841	0.1814	0.1785	0.1756	0.1724
2.500	0.1979	0.1957	0.1936	0.1914	0.1892	0.1869	0.1846	0.1822	0.1797	0.1770
2.857	0.1985	0.1969	0.1953	0.1937	0.1920	0.1903	0.1886	0.1868	0.1849	0.1827
3.000	0.1986	0.1972	0.1959	0.1944	0.1929	0.1913	0.1898	0.1881	0.1864	0.1845
3.333	0.1990	0.1978	0.1968	0.1955	0.1943	0.1931	0.1918	0.1905	0.1891	0.1875
3.750	0.1992	0.1984	0.1976	0.1967	0.1958	0.1949	0.1940	0.1930	0.1919	0.1908
4.000	0.1993	0.1987	0.1980	0.1973	0.1965	0.1958	0.1950	0.1941	0.1933	0.1925

$$\rho_A = \rho_1\left[1 + 2f\left(K, \frac{H}{A}\right)\right] \quad [4]$$

$$\rho_{1.2A} = \rho_1\left[1 + 2f\left(K, \frac{H}{1.2A}\right)\right] \quad [5]$$

$$\rho_{1.4A} = \rho_1\left[1 + 2f\left(K, \frac{H}{1.4A}\right)\right] \quad [6]$$

$$\rho_{1.6A} = \rho_1\left[1 + 2f\left(K, \frac{H}{1.6A}\right)\right] \quad [7]$$

$$\rho_{1.8A} = \rho_1\left[1 + 2f\left(K, \frac{H}{1.8A}\right)\right] \quad [8]$$

$$\rho_{2.0A} = \rho_1\left[1 + 2f\left(K, \frac{H}{2.0A}\right)\right] \quad [9]$$

Division of Eq. 4 by the sum of Eqs. 5, 6, 7, 8 and 9 gives

$$\frac{\rho_A}{\rho_{1.2A} + \rho_{1.4A} + \rho_{1.6A} + \rho_{1.8A} + \rho_{2.0A}} = \frac{1 + 2f\left(K, \frac{H}{A}\right)}{5 + 2\left[f\left(K, \frac{H}{1.2A}\right) + f\left(K, \frac{H}{1.4A}\right) + f\left(K, \frac{H}{1.6A}\right) + f\left(K, \frac{H}{1.8A}\right) + f\left(K, \frac{H}{2.0A}\right)\right]} \quad [10]$$

The ratio in Eq. 10 can be calculated* for any possible combination of K and $\frac{H}{A}$ values and master curves can be plotted (Fig. 3). Only two sets of master curves are necessary, one for the conducting bed and one for the insulating bed. Data for the plotting of the curves are given in Tables 1 and 2.

The application of the method is simple and can be explained by reference to Fig. 2. A value of A is chosen and the resistivity ratio (left-hand member of Eq. 10) is calculated. On referring to the master curves, a series of corresponding values of $\frac{H}{A}$ and K can be tabulated. Since A is known, these can be converted into a series of corresponding values of H and K, which can be plotted as a curve. Other values of A will result in similar curves. Theoretically, all of these curves should intersect at a single point whose coordinates determine the solution of the problem.

* For the computation, tables given by I. Roman[2] were of great assistance.

Analysis of Data

Study of Theoretical Curves

As a check on the correctness of the theory, the method was applied to data from two-layer curves. The interpretation in each case was definite and the results were accurate (Table 3).

In the analysis of three-layer curves, it was found that certain combinations of bed thickness and resistivity ratios responded very well to the method. Other combinations were much more difficult to interpret, and some extreme cases resulted in very inaccurate solutions, or no solution at all.

In general, a thin upper layer and an infinitely thick lower layer, separated by a bed of moderate thickness, proved to be a

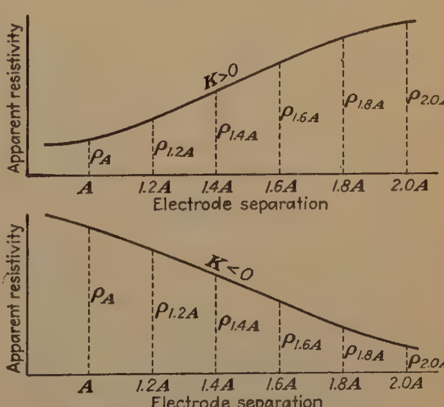

FIG. 2.—TWO-LAYER CURVES.

favorable case. If the resistivity of the lower bed was very large compared to the resistivities of the upper beds, the solutions were quite definite.

Apparently the four-layer problem can be solved partly for some combinations of

bed thicknesses and resistivity ratios. No attempt was made to solve for individual bed thickness, the three upper layers being considered as one bed, and the thickness of this composite stratum sought. Theoretical curves were taken from Watson's paper.[9]

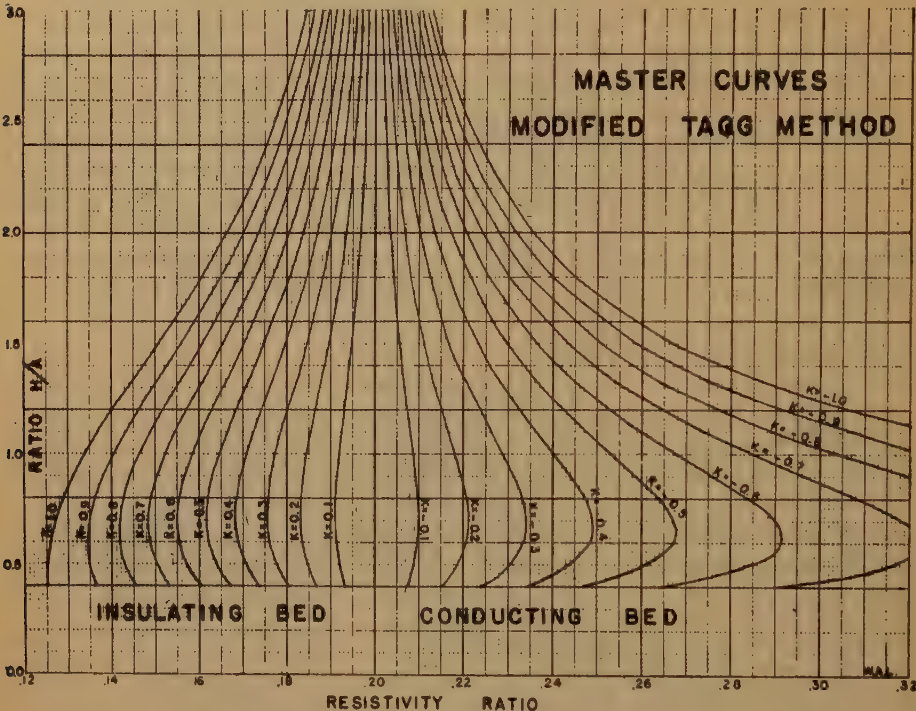

FIG. 3.—MASTER CURVES, MODIFIED TAGG METHOD.

TABLE 3.—*Two-layer Curves*

Source of Data	Known H, Ft.	Calculated H, Ft.	Known K	Calculated K	Interpretation
M.C.M. and T. *Bull.*,[a] Jan. 1932	100	101.6	0.667	0.678	Very good
Trans. A.I.M.E.[b]	100	100.1	0.800	0.800	Excellent

[a] C. H. Knaebel: Observation and Deduction Applicable to Measurement of Electrical Resistivity of Large Volumes of Earth in Place.
[b] I. Roman: *Trans.* A.I.M.E. (1934) 110, 183.

FIELD CURVES

The field data analyzed were obtained from a variety of sources and must necessarily represent a number of stratigraphic conditions. Some of the curves studied were obviously multilayer types and could not be expected to yield complete or definite interpretations. Others evidently were taken where the surface bedding and planes were not parallel, or where lateral changes in resistivity occurred, or both. It is perhaps surprising that such a large proportion of the field data, taken in many localities and by many observers, should lead to definite interpretation of depth to the underlying bed. This may be due to the fact that favorable stratigraphic conditions occur more generally than usually is assumed.

TABLE 4.—*Three-layer Curves*

Source of Data	Known H, Ft.	Calculated H, Ft.	Known K	Calculated K	Interpretation
Trans. A.I.M.E.[a]	36 216	35.3 218	−0.800 1.00	−0.789 0.995	Very good Very good

[a] R. J. Watson: *Trans.* A.I.M.E. (1934) 110, 220.

TABLE 5.—*Four-layer Curves*

Source of Data	Known H, Units	Calculated H, Units	Calculated K	Interpretation
Trans. A.I.M.E. (1934) 110, 224, curve 1	8	7.9	0.23	Fair
Trans. A.I.M.E. (1934) 110, 224, curve 4	8	Method failed		

Representative samples of the many field curves analyzed follow.

Tagg's Station B

Source: G. F. Tagg: *Trans.* A.I.M.E. (1934) 110, 141–144.
Station Location: Cleeve Hill Common, Cheltenham, Gloucestershire, England.
Structural Data: Thin bed of loam, limestone 50 to 266 ft. thick; deep bed of sand or clay.
Results given by Tagg:

$$H = 156 \text{ ft.}, \quad K = -0.6$$

Roman's analysis: $H = 200$ ft., $K = -0.85$

Method of Analysis	H, ft.	K	Interpretation
Tagg's second method	194	−0.73	Good
Modified Tagg method	198	−0.78	Good

Hubbert's Station I

Source: M. King Hubbert: *Trans.* A.I.M.E. (1934) 110, 25, 26.
Station Location: Southern Illinois, U.S.A.
Structural Data: Glacial drift, about 60 ft. thick, limestone bedrock.

Hubbert, using Tagg's first method, found the depth to the limestone to be 30 feet.

The modified Tagg method showed a few intersections of the H, K curves near the point 30, 0.75, but for the larger values of electrode separation there were many intersections near the point 57.5, 0.75. The small values of electrode separation are less dependable, as was evident from the study of the theoretical three-layer curves.

Hubbert's Station II

Source: M. King Hubbert: *Trans.* A.I.M.E. (1934) 110, 25, 26.
Station Location: Southern Illinois, U.S.A.
Structural Data: Glacial drift, about 100 ft. thick, limestone bedrock.

Tagg's first method, applied by Hubbert, led to a value of 46 ft. for the depth of the drift.

The H, K curves in the modified Tagg's method gave random intersection from $H = 54$ ft. to $H = 123$ ft. with a good group of intersections near 120 ft. The "best" point for the set of intersections was calculated and found to be $H = 106$ ft., $K = 0.688$.

Hubbert's Stations III *and* IV

Source: M. King Hubbert: *Trans.* A.I.M.E. (1934) 110, 25, 26.
Station Location: Southern Illinois, U.S.A.
Structural Data: Glacial drift, 90 ft. for station III, 160 ft. for station IV; shale bedrock.

Tagg's first method, applied by Hubbert, did not give good interpretations for either station. A few intersections indicated a depth of overburden of about 50 ft. at station IV.

The modified Tagg method also failed to solve for the thickness of the overburden. For station III the H, K curves failed to intersect, and for station IV there were only two intersections, one at the point 101, −0.42, and one at 125, −0.46.

Evidently the actual structure is not nearly enough that assumed in the theory, and no interpretation other than a qualitative one can be made.

Pioneer Oil Co. Resistivity Curve

Source: I. E. Rosenzweig: A New Method of Depth Determination in Earth-resistivity

Measurements. *Trans.* A.I.M.E. (1940) 138, 416.

Station Location: Lwow, Poland.

Rosenzweig used his method, involving the use of a set of master curves and the solving of sets of simultaneous equations to find

$$H = 36.1 \text{ meters}, \qquad K = -0.52$$

These values were checked by Rosenzweig by means of Tagg's second method; the results,

$$H = 33 \text{ meters}, \qquad K = -0.57$$

were in good agreement with the results given above.

The modified Tagg method led to the values

$$H = 35.3 \text{ meters}, \qquad K = -0.60$$

The interpretation of the family of intersections was clear and definite. Unfortunately, no structural data were available.

Greenwood Diamond-drill Hole No. 18

Source: Geophysical files of the Mathematics and Physics Department of the Michigan College of Mining and Technology.

Station Location: Near Ishpeming, iron country of northern Michigan.

Structural Data: Glacial drift 140 ft. thick over bedrock.

Resistivity Data:

Electrode Separation, Ft.	Apparent Resistivity, Ohm-cm.
100	19,390
120	20,970
140	23,210
160	25,650
180	29,080
200	32,520
220	34,370
240	36,720
260	39,260
280	41,560

By Tagg's second method,

$$H = 135 \text{ ft.}, \qquad K = 0.95$$

By the modified Tagg's method,

$$H = 133 \text{ ft.}, \qquad K = 0.95$$

The interpretation was definite, especially so in the modified method.

Indiana Diamond-drill Hole No. 11

Source: Geophysical files of the Mathematics and Physics Department of the Michigan College of Mining and Technology.

Station Location: Houghton County, copper country of northern Michigan.

Structural Data: Glacial drift, approximately 120 ft. thick, Keweenawan flows.

Resistivity Data:

Electrode Separation, Ft.	Apparent Resistivity, Ohm-cm.
40	7,510
60	10,560
80	13,470
100	16,430
120	18,710
140	21,220
160	23,920
180	27,020
200	29,170
220	31,390
240	33,330
260	35,080
280	36,610
300	38,110
320	39,300
340	40,410
360	41,600

Roman[3] analyzed this curve for separations up to 200 ft. and found the thickness of the upper bed to be 33.9 ft. The upper layer had a calculated resistivity of 4730 ohm-cm. and the second a calculated resistivity of 90,000 ohm-cm.

The second method of Tagg led to a good agreement with the above solution. For the larger electrode separations a depth to a third bed was calculated as 106 ft., with a reflection factor 0.96.

The modified Tagg method indicated that the depth to the third layer is 100 ft. with a reflection factor of 0.96, leading to the conclusion that the third-layer resistivity is of the order of 600,000 ohm-cm.

Summary

A method of analysis of simple types of resistivity curves has been explained and illustrated by application to theoretical data and actual resistivity-survey results. For comparison, other methods of analysis have been applied to the same data.

Tables of figures and the corresponding master curves have been included. The figures are accurate enough to justify second-order interpolation even though this should very rarely be necessary.

The measuring configuration is assumed to be the Wenner four-electrode system, though minor modifications might permit the use of other configurations.

The field data should be carefully taken, preferably with equipment utilizing the potentiometer principle, and due attention should be paid to possible disturbing elements such as pipe lines, wire fences, railway tracks. At any station where a depth is to be computed, resistivity lines should be run in several azimuths, and the apparent resistivities for like electrode separations averaged to minimize lateral inhomogeneity effects. If the resistivity curves for the various azimuths differ greatly, a good interpretation of depth is seldom possible. In such cases comparison with near-by control stations may prove of value.

A fifth electrode at the center of the system (the Lee configuration) is often used. This serves to detect lateral asymmetry due to nonparallel bedding or other types of digression from the structure assumed in the theory.

Since the extremities of the resistivity curve are usually of most value in depth determination, it is often necessary to use small increments of electrode separation for the first portion of the curve, and to extend the separation to a value several times the estimated depth to the underlying bed.

The resistivity curves plotted from field data are often jagged and irregular. It is usually advisable to remove the minor irregularities by some process of smoothing, since the small variations are probably caused by local changes in the overburden. The smoothing of the resistivity curve seems to be of less importance in the modified Tagg method than in others studied, perhaps because of the combining of apparent resistivities along the curve, and the consequent averaging effect.

The data presented in this paper have been selected as representative of the many analyses attempted. Where structural conditions are favorable, interpretation is often definite and accurate. The unfavorable cases are easily identified, and no attempt should be made to force a solution, as only an interpretation of a qualitative nature is feasible.

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References

1. W. A. Longacre: Thesis submitted to Michigan College of Mining and Technology, April 1941.
2. I. Roman: Some Interpretations of Earth-resistivity Data. *Trans.* A.I.M.E. (1934) **110**, 183.
3. G. F. Tagg: (*a*) Interpretation of Resistivity Measurements. *Trans.* A.I.M.E. (1934) **110**, 135. (*b*) Interpretation of Earth-resistivity Curves. *Trans.* A.I.M.E. (1940) **138**, 399.
4. F. C. Wenner: A Method of Measuring Earth Resistivity. Nat. Bur. Stds. *Sci. Paper* 258 (1915).
5. J. Fisher: Notes on Geophysics. Michigan College of Mining and Technology, 1935.
6. I. Roman: How to Compute Tables for Determining the Electrical Resistivity of Underlying Beds and their Application to Geophysical Problems. U.S. Bur. Mines *Tech. Paper* 502 (1931).
7. J. N. Hummel: A Theoretical Study of Apparent Resistivities in Surface Potential Methods. *Trans.* A.I.M.E. (1932) **97**, 392.
8. S. J. Pirson: Interpretation of Three-layer Resistivity Curves. *Trans.* A.I.M.E. (1934) **110**, 148.
9. R. J. Watson: A Contribution to the Theory of the Interpretation of Resistivity Measurements Obtained from Surface Potential Observations. *Trans.* A.I.M.E. (1934) **110**, 201.

Calculation of the Depth of a Magnetic Deposit

By Janshi Sen,* Member A.I.M.E.

(New York Meeting, February 1943)

Vertical-intensity magnetometers, for instance the Hotchkiss Superdip and the Askania vertical field balance, are now widely used, because vertical-intensity charts give definite information for the location of upper pole, dip and strike, and approximate shape of the deposit. Again, a slow and steady increase of dip over a large area indicates a large deep-lying deposit, while a large dip limited to a small area and falling away rapidly suggests a small and shallow one. The complication comes more from the richness of the ore. A large body of lean ore near the surface might produce the same vertical-intensity chart as a rich ore at depth. This paper presents a method for calculating the maximum depth of a single-pole deposit and another for a two-pole mineral body, by utilizing data of both vertical and horizontal intensities as obtained by a Thalen-Tiberg magnetometer.

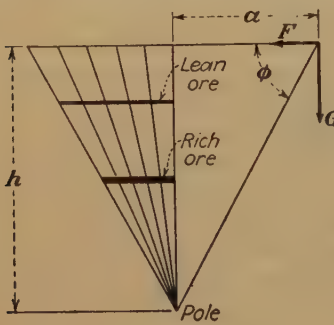

Fig. 1.

As shown on the left side of Fig. 1, lean ore, rich ore and a single pole produce the same magnetic field. The depth of the pole, h, can be calculated from the following relation:

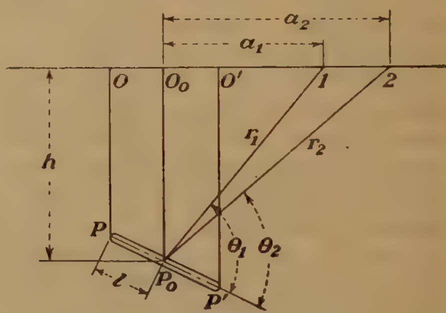

Fig. 2.

$$h \div a = \tan \phi = G \div F$$
$$h = a \times \frac{G}{F},$$

where G is the vertical intensity at point A due to the pole; F, the horizontal intensity of the same; and a, the distance from the point of maximum vertical intensity or the vertical projection of the pole on the surface to the point of observation A.

If an entirely covered deposit is indicated by magnetic measurements and boring cost estimated from the calculated depth is so reasonable as to encourage drilling, the ore should be struck somewhere within the limit of the calculated depth by the borehole. A number of such points as A should be taken for calculation, erratic results should be rejected and the average figure used for cost estimation.

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When a center of maximum negative vertical intensity is exposed on the chart, the depth of the deposit can be more definitely ascertained by utilization of both vertical and horizontal intensities. In Fig. 2, P_o is the middle-point between the upper pole P and the lower pole P'; O, O_o and O', the vertical projections of P, P_o and P' on the surface; 1 and 2, the points of observation; l, the half length of the equivalent magnet of the deposit and h, the depth of mid point of the centers of the two poles of the deposit.

Let G and G_2 be the vertical intensities at points 1 and 2; F_1 and F_2, the horizontal intensities; and I_1 and I_2, the total intensities.

Then:

$$I_1 = \sqrt{G_1^2 + F_1^2}$$
$$I_2 = \sqrt{G_2^2 + F_2^2}$$

From formulas in textbooks of physics or magnetism and electricity, it may be written:

$$I_1 = \sqrt{\left(\frac{2M \cos \theta_1}{r_1^3\left[1 + \left(\frac{l}{r_1}\right)^4 - 2\left(\frac{l}{r_1}\right)^2\right]}\right)^2 + \left(\frac{M \sin \theta_1}{r_1^3\left[1 + \left(\frac{l}{r_1}\right)^2\right]^{3/2}}\right)^2}$$

$$I_2 = \sqrt{\left(\frac{2M \cos \theta_2}{r_2^3\left[1 + \left(\frac{l}{r_2}\right)^4 - 2\left(\frac{l}{r_2}\right)^2\right]}\right)^2 + \left(\frac{M \sin \theta_2}{r_2^3\left[1 + \left(\frac{l}{r_2}\right)^2\right]^{3/2}}\right)^2}$$

where M is the moment of the equivalent magnet.

Taking r_1 and r_2 sufficiently long as compared with l, the terms involving l may be dropped. The error in dropping these terms is somewhat compensating, as they make the first or cosine-term larger and the second term smaller.

Then:

$$I_1 = \sqrt{\left(\frac{2M \cos \theta_1}{r_1^3}\right)^2 + \left(\frac{M \sin \theta_1}{r_1^3}\right)^2} = \frac{M}{r_1^3}\sqrt{3 \cos^2 \theta_1 + 1}$$

$$I_2 = \sqrt{\left(\frac{2M \cos \theta_2}{r_2^3}\right)^2 + \left(\frac{M \sin \theta_2}{r_2^3}\right)^2} = \frac{M}{r_2^3}\sqrt{3 \cos^2 \theta_2 + 1}$$

Since $(a_2 - a_1)$ is very small compared with r_1 and r_2, θ_1, and θ_2 may be considered equal.

Then:

$$I_1 \div I_2 = r_2^3 \div r_1^3$$

$$r_1^2 = r_2^2\left(\frac{I_2}{I_1}\right)^{2/3} \qquad [1]$$

$$r_2^2 = r_1^2\left(\frac{I_1}{I_2}\right)^{2/3} \qquad [2]$$

Now:

$$h^2 = r_1^2 - a_1^2 \qquad [3]$$
$$h^2 = r_2^2 - a_2^2 \qquad [4]$$
$$r_1^2 = r_2^2 - (a_2^2 - a_1^2) \qquad [5]$$
$$r_2^2 = r_1^2 + (a_2^2 - a_1^2) \qquad [6]$$

Substitute Eqs. 1 and 2 in Eqs. 5 and 6:

$$r_1^2 = r_1^2\left(\frac{I_1}{I_2}\right)^{2/3} - (a_2^2 - a_1^2)$$

$$r_2^2 = r_2^2\left(\frac{I_2}{I_1}\right)^{2/3} + (a_2^2 - a_1^2)$$

$$r_1\left[1 - \left(\frac{I_1}{I_2}\right)^{2/3}\right] = a_1^2 - a_2^2$$

$$r_2\left[1 - \left(\frac{I_2}{I_1}\right)^{2/3}\right] = a_2^2 - a_1^2$$

$$r_2^2 = (a_1^2 - a_2^2) \div \left[1 - \left(\frac{I_1}{I_2}\right)^{2/3}\right] \qquad [7]$$

$$r_2 = (a_2^2 - a_1^2) \div \left[1 - \left(\frac{I_2}{I_1}\right)^{2/3}\right] \qquad [8]$$

Substitute Eqs. 7 and 8 into Eqs. 3 and 4:

$$h^2 = \frac{a_1^2 - a_2^2}{1 - \left(\frac{I_1}{I_2}\right)^{2/3}} - a_1^2$$

$$h^2 = \frac{a_2^2 - a_1^2}{1 - \left(\frac{I_2}{I_1}\right)^{2/3}} - a_2^2$$

$$2h^2 = \frac{a_1^2 - a_2^2}{1 - \left(\frac{I_1}{I_2}\right)^{2/3}} + \frac{a_2^2 - a_1^2}{1 - \left(\frac{I_2}{I_1}\right)^{2/3}} - (a_1^2 + a_2^2)$$

$$= (a_2^2 - a_1^2)\,\frac{I_1^{2/3} + I_2^{2/3}}{I_1^{2/3} - I_2^{2/3}} - (a_1^2 + a_2^2)$$

$$h = \sqrt{\frac{a_2^2 - a_1^2}{2} \times \frac{I_1^{2/3} + I_2^{2/3}}{I_1^{2/3} - I_2^{2/3}} - \frac{a_1^2 + a_2^2}{2}}$$

The points 1 and 2 are on a line through O and O' produced; a number of such pairs of points should be taken for check and the result from the farthest pair employed to estimate boring cost. The higher the susceptibility of the deposit and the more sensitive the instrument, the more accurate is the depth calculated.

If a line instead of a point of maximum vertical intensity is exposed on the chart, the first simple equation is applied, but the observation points should be taken on a line perpendicular to the magnetic axis. Similarly, the second equation is employed when two lines of maximum positive and maximum negative vertical intensities are depicted. Consequently, these two equations cover virtually all cases of depth calculation of prospecting by observations on both vertical and horizontal magnetic intensities of mineral deposits.

DISCUSSION

D. C. Skeels.*—The formulas developed by Professor Sen involve both vertical and horizontal intensity. It should be pointed out that the depth to a pole or dipole can be determined from vertical measurements alone, by utilizing the width of the vertical intensity anomaly. In fact, if sufficient vertical data are available, the horizontal intensity can be calculated from the vertical data, by an application of Green's theorem. Therefore, when enough vertical data are available to define the anomaly, the value of making a horizontal survey is questionable.

On the other hand, there are special conditions (as, for example, underground, or near a body of water) in which it is impossible to obtain enough vertical data to define the anomaly completely. In these cases the formulas developed by Mr. Sen may have a practical application.

The statement in the last paragraph that "the second equation is to be applied when two lines of maximum positive and maximum negative vertical intensities are depicted" is not justified, because in the latter case a line of dipoles is indicated rather than a single dipole, and the equations developed for a single dipole do not apply.

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Relation between Spontaneous Polarization Curves and Depth, Size, and Dip of Ore Bodies

By Walter Stern*

(New York Meeting, February 1943)

The self-potential or spontaneous polarization method is one of the oldest in the field of electrical exploration. When applied in prospecting for ore bodies, it is one of the most rapid and inexpensive means of locating indications of ore bodies at shallow depth. Usually, the procedure is to survey the equipotential lines of the electrical field that is generated by the electrochemical activity of the ore near the ground-water level, and to localize the so-called *negative centers* or points of greatest negative anomaly. Another field procedure involves the measurement of potential differences along potential profiles, generally laid out at right angles to the assumed strike. Again, in such survey, the basis for establishing the presence of ore is the location of negative potential anomalies.

The earlier writers on the subject, notably Schlumberger[1] and R. C. Wells,[2] did much to clarify the fundamental electrochemical phenomena involved. Interpretation of the field data, however, remained largely qualitative. In 1925, A. Petrovsky[3] analyzed the relation between the shape of the potential anomaly curve and size and depth of an ore body by assuming the subsurface body to be a polarized sphere.[4] Along similar lines of approach, Edge and Laby[5] considered the ore body a dipping sheet with limited extent in the direction of strike, while Poldini[6] based the theory on the assumption of a dipping bar.

The following study endeavors to enlarge upon these earlier investigations and attempts, on the basis of the potential distribution of a polarized bar, to indicate certain characteristics of the anomaly curve that make possible the determination of depth, size and dip of a subsurface body.

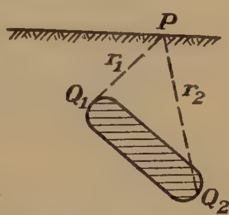

Fig. 1.—Ore body considered as dipole.

The Spontaneous Polarization Field Set Up by an Ore Body

If a sulphide ore body is subjected to oxidation varying in degree in its upper and lower parts according to the difference in the concentration of oxygen within the surrounding medium, an electrical potential field is set up. The form and distribution of this field will be investigated herein with special reference to its components on the earth's surface.

Under the simplifying assumption that the ore body may be considered as a dipole with the point sources Q_1 and Q_2 situated at its upper and lower ends (Fig. 1), the potential of the spontaneous polarization at point P is given by the following equation:

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1 References are at the end of the paper.

$$\phi_P = \frac{1}{r_1} - \frac{1}{r_2} \qquad [1]$$

where

$$r_1 \equiv \overline{PQ_1}$$
$$r_2 \equiv \overline{PQ_2}$$

By calculating ϕ_P for a sufficient number of points ($P_1P_2P_3 \ldots$) it is possible to draw the equipotential lines of the spontaneous polarization field. This is done in Fig. 2, where the lower diagram (vertical section) shows the field distribution while the upper diagram indicates the potential curve $\phi_P = f(x)$ along the line AA' representing the earth's surface.

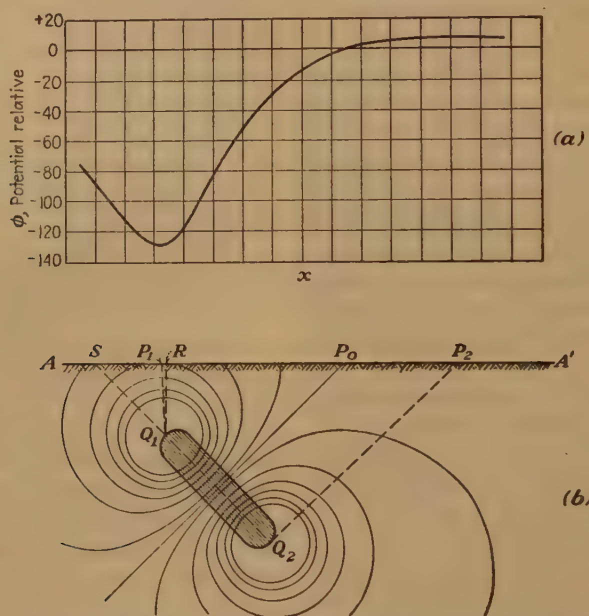

Fig. 2.—*a*. Curve of potentials of spontaneous polarization along line at earth's surface $\phi = f(x)$; *b*. Subsurface equipotential lines of spontaneous polarization field of ore body ($D/L = 0.5$, $\alpha = 45°$).

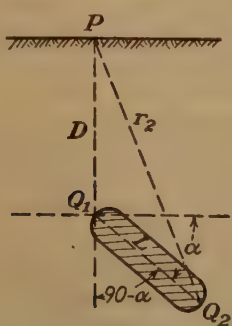

Fig. 3.—Relation of depth D, axial length L and dip A of ore body to ϕP.

Position of Ore Body and Strength of Spontaneous Polarization

Using Eq. 1, the respective values may be calculated for ϕ_P in relation to depth D, axial length L and dip α of the ore body (Fig. 3). Calculations may first be confined to a point P situated above Q_1 on the earth's surface. Since $r_1 \equiv D$, Eq. 1 may be written:

$$\phi_P = \frac{1}{D} - \frac{1}{r_2} \qquad [2]$$

wherein

$$r_2 = \sqrt{D^2 + L^2 - 2DL\cos(90 + \alpha)}$$
$$= \sqrt{D^2 + L^2 + 2DL\sin\alpha}$$

thus obtaining for ϕ_P:

$$\phi_P = \frac{1}{D} - \frac{1}{\sqrt{D^2 + L^2 + 2DL\sin\alpha}} \qquad [3]$$

Consider the following cases separately:

$$\phi_P = f(D), \quad L = 1, \quad \alpha = \text{constant}$$
$$\phi_P = f(L), \quad D = 1, \quad \alpha = \text{constant}$$
$$\phi_P = f(\alpha), \quad D = 1, \quad L = \text{constant}$$
$$\phi_P = f(\alpha), \quad L = 1, \quad D = \text{constant}$$

The influence of each of these components on ϕ_P may be determined. The results are shown in Tables 1 and 2 and in Figs. 4, 5, 6 and 7. From these results the following conclusions may be drawn:

1. The strength of the spontaneous polarization on the earth's surface is mainly governed by the depth of the ore body (Fig. 4). While strong spontaneous polarization values will still be obtained for $D/L = 1$, rapid decrease of ϕ_P with the continued increase of D/L will be noticed, thus limiting the depth range from which indications can be expected. This limit might practically be reached by $D/L = 2$.

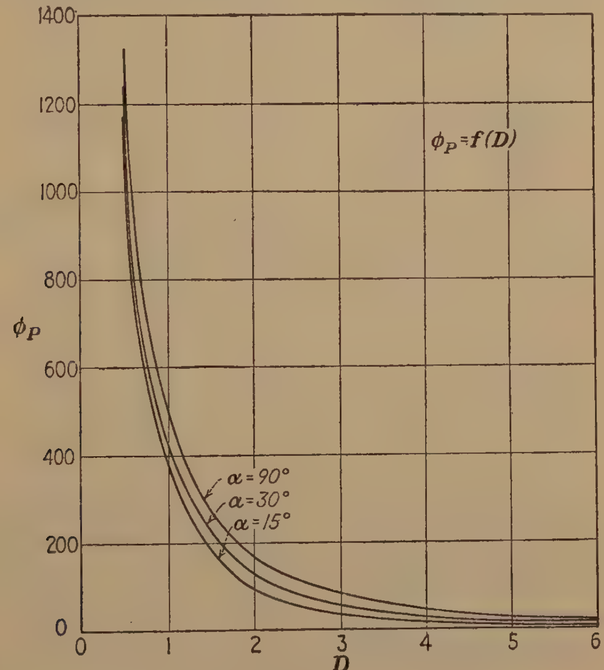

FIG. 4.—EFFECT OF DEPTH.

TABLE 1.—*Influence of Depth D of Ore Body on Strength ϕ_P of Spontaneous Polarization ($L = 1$)*

α	D: 0.5	1	2	3	4	5	6
	ϕ_P						
15°	1185.9	369.8	93.0	39.1	21.0	13.0	8.8
30°	1244.1	422.7	122.0	56.0	31.8	20.4	14.2
60°	1312.6	482.4	156.3	76.8	45.6	30.1	21.4
90°	1333.3	500.0	166.7	83.3	50.0	33.3	23.8

TABLE 2.—*Influence of Length L of Ore Body on Strength ϕ_P of Spontaneous Polarization ($D = 1$)*

α	L: 0.5	1	2	3	4	5	6
	ϕ_P						
15°	185.9	369.8	593.0	705.5	771.1	813.0	842.1
30°	244.1	422.7	622.0	722.7	781.8	820.4	847.5
45°	285.2	458.8	642.6	735.0	789.9	826.1	851.7
60°	312.6	482.4	656.3	743.5	795.6	830.1	854.7
90°	333.5	500.0	666.7	750.0	800.0	833.3	857.1

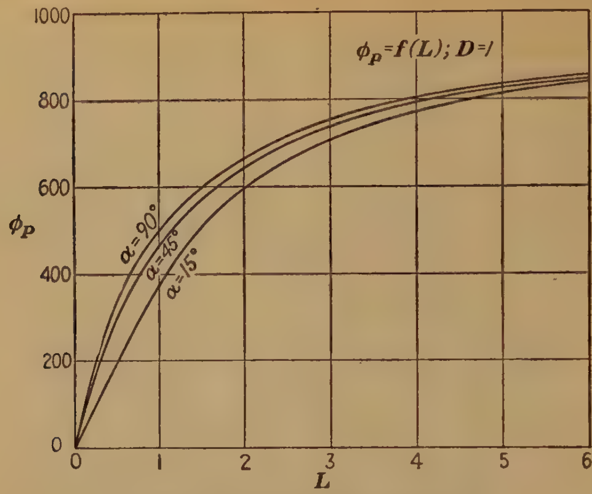

FIG. 5.—EFFECT OF AXIAL LENGTH.

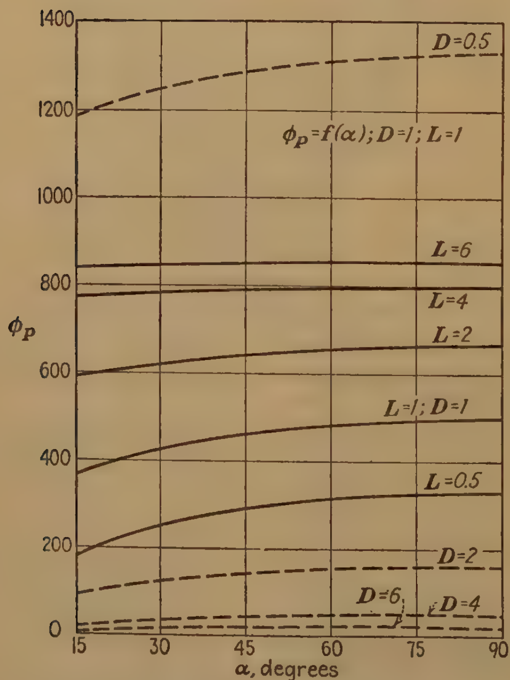

FIG. 6.—EFFECT OF DIP OF ORE BODY.

2. The axial length of the ore body produces an opposite effect, ϕ_P increasing with increasing length (Fig. 5). But here too the effect is limited. After the initial rapid increase of ϕ_P with increasing L/D the influence of L decreases on a progressive scale with the continued increase of L. No major influence will be felt from $L/D = 2$, loses its significance, disappearing almost when $L/D = 4$ and $D/L = 4$.

Position of Ore Body and Distribution of Spontaneous Polarization on Earth's Surface

Let us investigate $\phi_P = f(x)$; i.e., the potential distribution of the spontaneous

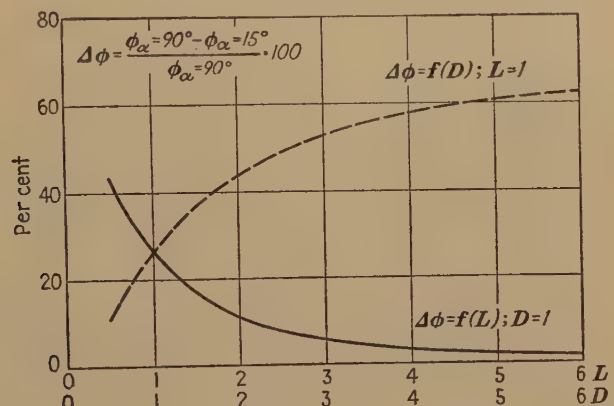

Fig. 7.—Effect of dip of ore body.

ϕ_P having reached approximately 65 per cent of its ultimate value for $L/D = \infty$.

3. The influence of the dip of the ore body on ϕ_P (Figs. 6 and 7) increases

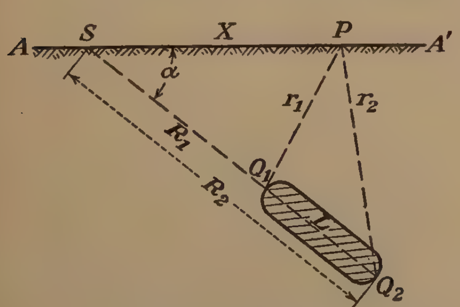

Fig. 8.—Potential distribution of spontaneous polarization.

x = distance of points along earth's surface from intersection S with prolonged axis of ore body.

absolutely with the decrease of depth and length, and relatively with the increase of D and the decrease of L. This influence is still considerable for $L/D = 1$ but soon

polarization along the line AA' (Fig. 8), where x expresses the distance of each point $P, P_1, P_2 \ldots$ along the earth's surface from its intersection S with the prolonged axis of the ore body. Restating Eq. 1 by introducing x:

$$\phi_P = \frac{1}{\sqrt{x^2 + R_1^2 - 2xR_1 \cos\alpha}} - \frac{1}{\sqrt{x^2 + R_2^2 - 2xR_2 \cos\alpha}} \qquad [4]$$

since

$$r_1 = \sqrt{x^2 + R_1^2 - 2xR_1 \cos\alpha}$$
$$r_2 = \sqrt{x^2 + R_2^2 - 2xR_2 \cos\alpha}$$

where

$$R_1 \equiv \overline{SQ_1}$$
$$R_2 \equiv \overline{SQ_2} = R_1 + L$$

From the first derivative of Eq. 4,

$$\frac{d\phi_P}{dx} = \frac{x - R_2 \cos\alpha}{\sqrt{(x^2 + R_2^2 - 2xR_2 \cos\alpha)^3}} - \frac{x - R_1 \cos\alpha}{\sqrt{(x^2 + R_1^2 - 2xR_1 \cos\alpha)^3}}. \qquad [5]$$

The coordinates of the two singular points of the spontaneous polarization curve, i.e., the (negative) minimum at P_1 and the (positive) maximum at P_2, are determined by

$$\frac{d\phi_{P_1}}{dx_1} = 0, \ \frac{d^2\phi_{P_1}}{dx_1^2} \text{ negative} \qquad [6]$$

$$\frac{d\phi_{P_2}}{dx_2} = 0, \ \frac{d^2\phi_{P_2}}{dx_2^2} \text{ positive} \qquad [7]$$

Also,

$$\phi_{P_1} = \frac{1}{\sqrt{x_1^2 + R_1^2 - 2x_1R_1 \cos\alpha}} - \frac{1}{\sqrt{x_1^2 + R_2^2 - 2x_1R_2 \cos\alpha}} \qquad [8]$$

$$\phi_{P_2} = \frac{1}{\sqrt{x_2^2 + R_1^2 - 2x_2R_1 \cos\alpha}} - \frac{1}{\sqrt{x_2^2 + R_2^2 - 2x_2R_2 \cos\alpha}} \qquad [9]$$

The position of the neutral point P_0 is given by

$$\phi_{P_0} = \frac{1}{\sqrt{x_0^2 + R_1^2 - 2x_0R_1 \cos\alpha}} - \frac{1}{\sqrt{x_0^2 + R_2^2 - 2x_0R_2 \cos\alpha}} = 0 \qquad [10]$$

from which

$$x_0 = \frac{R_1 + R_2}{2 \cos\alpha} \qquad [11]$$

The approximate solutions for x_1, x_2, x_0, and ϕ_{P_1} ϕ_{P_2} for different parameters of D/L and α are given in Tables 3, 4 and 5.

From the results given in Tables 3, 4 and 5, important relations may be found between the geophysical data and the position of the ore body. For this purpose it is well to introduce two parameters: (1) the potential ratio; i.e., the ratio between the (negative) potential minimum and the (positive) potential maximum,

$$R_P = \frac{\phi_{P_1}}{\phi_{P_2}} \qquad [12]$$

and (2) the distance ratio; i.e., the ratio of the distance between the (negative) minimum and the equipotential line O (neutral

TABLE 3.—*Influence of Depth D, Length L, and Dip α of Ore Body on Position x_1 and Strength ϕ_{P_1} of Minimum or Negative Center of Spontaneous Polarization*

D/L	α 15°	30°	45°	60°
	x_1			
0.5	18.04	8.19	4.68	2.68
1	34.8	15.53	8.74	5.0
1.5	51.2	22.5	12.6	7.16
	ϕ_{P_1}			
0.5	1208.3	1252.5	1289.5	1314.3
1	398.6	437.4	465.6	484.9
1.5	195.6	221.6	241.9	256.0

TABLE 4.—*Influence of Depth D, Length L, Dip α of Ore Body on Position x_2 and Strength ϕ_{P_2} of Maximum or Positive Center of Spontaneous Polarization*

D/L	α 15°	30°	45°	60°
	x_2			
0.5	31.05	23.9	24.72	31.75
1	53.75	38.14	38.0	48.3
1.5	76.7	52.8	51.9	65.0
	ϕ_{P_2}			
0.5	490.8	212.0	80.3	22.3
1	177.3	84.9	33.9	9.7
1.5	90.2	45.3	18.4	5.4

TABLE 5.—*Influence of Depth D, Length L, Dip α of Ore Body on Position x_0 of Neutral Point P_0 of Spontaneous Polarization*

D/L	α 15°	30°	45°	60°
	x_0			
0.5	25.18	17.32	17.07	21.55
1	45.18	28.87	27.07	33.04
1.5	65.18	40.42	37.07	44.64

point P_0) and that between the (positive) maximum and the neutral point,

$$R_D = \frac{x_0 - x_1}{x_2 - x_0} \qquad [13]$$

Calculating R_P and R_D from the quantities of Tables 3, 4 and 5, the results given in Table 6 and Fig. 9 are obtained, which indicate that by the potential ratio R_P, D/L is determined if α is known, the latter being given by the distance ratio R_D, which yields α independently of D/L.

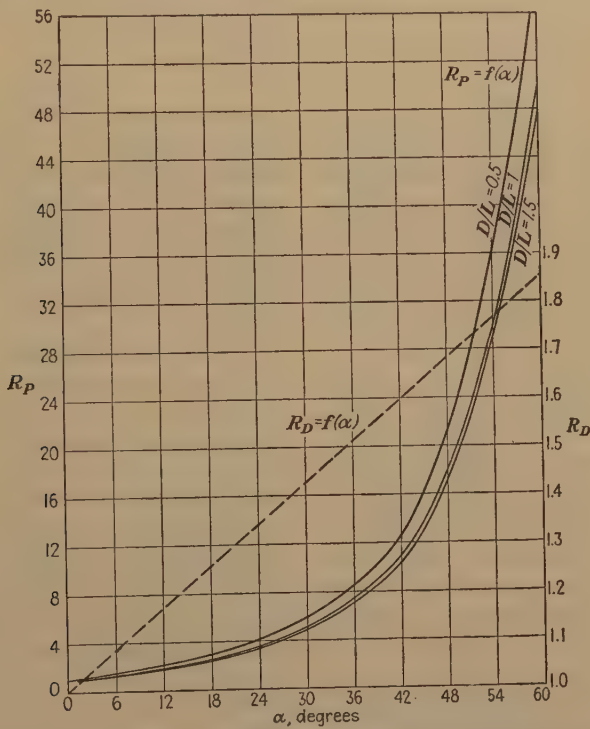

FIG. 9.—R_P AND R_D IN RELATION TO DEPTH, LENGTH AND DIP OF ORE BODY. (MASTER DIAGRAM.)

The results of Table 6 may be considered as general solutions of the problem, provided that the simplifying assumptions adopted in this theory are justified in practice. Fig. 9 may accordingly be used as a master diagram for analyzing results.

Finally, the "prospecting angle" $\beta = \measuredangle P_0P_1Q_1$ (Table 7) may be obtained from

$$\tan \beta = \frac{D}{\sqrt{R_1^2 - D^2} - x_1} \qquad [14]$$

which is the angle under which Q_1 appears in relation to P_1. Further, the "factor of intersection" k (Table 8),

$$k = \frac{x_0 - x_1}{x_1} \qquad [15]$$

gives the point S of intersection between the prolonged axis of the ore body and the earth's surface. Thus, all means have been furnished for tracing the position (depth, length and dip) of the ore body as shown in

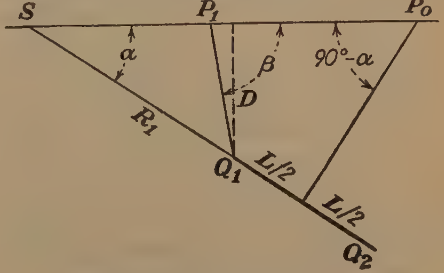

FIG. 10.—POSITION OF ORE BODY.

Fig. 10, provided the topography of the area surveyed is sufficiently regular. The treatment of cases where the topography is irregular requires further investigation.

TABLE 6.—*Potential Ratio R_P and Distance Ratio R_D in Relation to Depth, Length and Dip of Ore Body*

D/L	α 15°	α 30°	α 45°	α 60°
	R_P			
0.5	2.462	5.899	16.054	58.921
1	2.248	5.151	13.719	49.99
1.5	2.170	4.892	13.147	47.408
	R_D			
0.5	1.215	1.400	1.620	1.829
1	1.210	1.438	1.677	1.848
1.5	1.213	1.447	1.650	1.841

TABLE 7.—*Prospecting Angle β in Relation to Depth, Length and Dip of Ore Body*

D/L	α 15°	α 30°	α 45°	α 60°	α 90°
	β				
0.5	82°56′	84°38′	86°20′	87°38′	90°00′
1	75°51′	79°51′	82°49′	85°35′	90°00′
1.5	72°18′	76°56′	80°55′	84°17′	90°00′

TABLE 8.—*Intersection Factor k in Relation to Depth, Length and Dip of Ore Body*

D/L	α 15°	α 30°	α 45°	α 60°
	k			
0.5	0.40	1.12	2.65	7.04
1	0.30	0.86	2.10	5.61
1.5	0.27	0.80	1.94	5.24

The successful application of this method requires a comparatively high degree of accuracy in surveying the positions and potentials of the spontaneous polarization centers and in determining the equipotential line O, and necessitates the use of special methods of corrections. These, however, will be dealt with in a separate paper.

Summary

The relations between the position (depth, size and dip) of an ore body and the elements of a spontaneous polarization field produced by it are investigated with a view to evolving a method by which the first can be determined if the latter are known.

A study of the influence of depth, size and dip of the ore body on strength and distribution of the spontaneous polarization on the earth's surface yields the following characteristic parameters: (1) the relative strength, and (2) the respective distances between the potential maximum and minimum (negative and positive centers) and the position of the equipotential line O. They are expressed by two ratios, the Potential Ratio and the Distance Ratio, from which the data required for defining the position of the ore body can be obtained.

References

1. C. Schlumberger: Etude sur la prospection électrique du sous sol. Paris, 1920. Gauthier Villars.
2. R. C. Wells: Electrical Activity in Ore Deposits. U. S. Geol. Survey *Bull.* 548 (1914).
3. A. Petrovsky: Inst. Prac. Geophys. *Bull.* 1 (Leningrad, 1925) 87.
4. C. A. Heiland: Geophysical Exploration, 672–675. New York, 1940. Prentice-Hall.
5. A. B. Edge and T. H. Laby: The Principles and Practice of Geophysical Prospecting, 244. Cambridge, 1931.
6. E. Poldini: Univ. de Lausanne *Bull.* 61 (1938) 21.

An Empirical Method of Interpretation of Earth-resistivity Measurements

By R. Woodward Moore*

(New York Meeting, February 1944)

Abstract

A graphical method of analyzing the data obtained from shallow earth-resistivity depth tests is presented. The method is based upon empirical results and has no theoretical basis. The usual apparent resistivity-electrode spacing curve is used together with a cumulative resistivity-electrode spacing curve plotted on the same sheet. The greatly reduced scale required for plotting the cumulative values of resistivity together with the effect of the summation of the individual resistivity values serves to minimize the effect of purely local surface anomalies and inadvertent errors of measurement. The point of intersection of tangents or straight lines drawn to intersect at zones of maximum curvature in the cumulative curve indicates the depth to the underlying material. Numerous figures are presented in which data from published reports and from recent field studies are analyzed and the results compared with actual depths established by borings or with depth values obtained by the use of theoretical methods of analysis. Smoothly rounded curves of apparent resistivity such as are often obtained in the field, and which have been a serious drawback to attempts to analyze the data empirically heretofore, appear to be susceptible to rather accurate analysis by the method described.

The method is best suited to analyses involving shallow two-layer formations. It has been applied successfully, however, in analyzing the data obtained from tests made over shallow three-layer formations. As with most empirical methods, its chief advantage is its simplicity and ease of application.

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Introduction

There have been published many papers that discuss the interpretation of data obtained from earth-resistivity tests when using the four-terminal method of electrode spacing developed by Wenner.[1] The majority of these have dealt with theoretical analyses for two-layer and three-layer formations. Some sets of "master curves" have been presented for use in analyzing field data to determine the depth to the first and possibly the second horizon below the earth's surface. Although practically all of these theoretical methods of analysis have appeared to have particular merit and some have been used successfully in practice, they have been found to be of little value where the local conditions surrounding the test failed to conform to those assumed in the theory.

In certain fields, particularly in civil engineering, relatively shallow explorations are often involved and geophysical methods of test must compete with the direct methods of exploration ordinarily used. Only when it can be demonstrated that geophysical methods of test can materially reduce the time and cost of a given exploration project will the civil engineer abandon direct methods in favor of the interpretations of geophysical exploration data.

Empirical methods of analyzing earth-resistivity data have been used in many instances in the past. Such methods have been employed for a number of years by the Public Roads Administration in research work relative to the application of

[1] References are at the end of the paper.

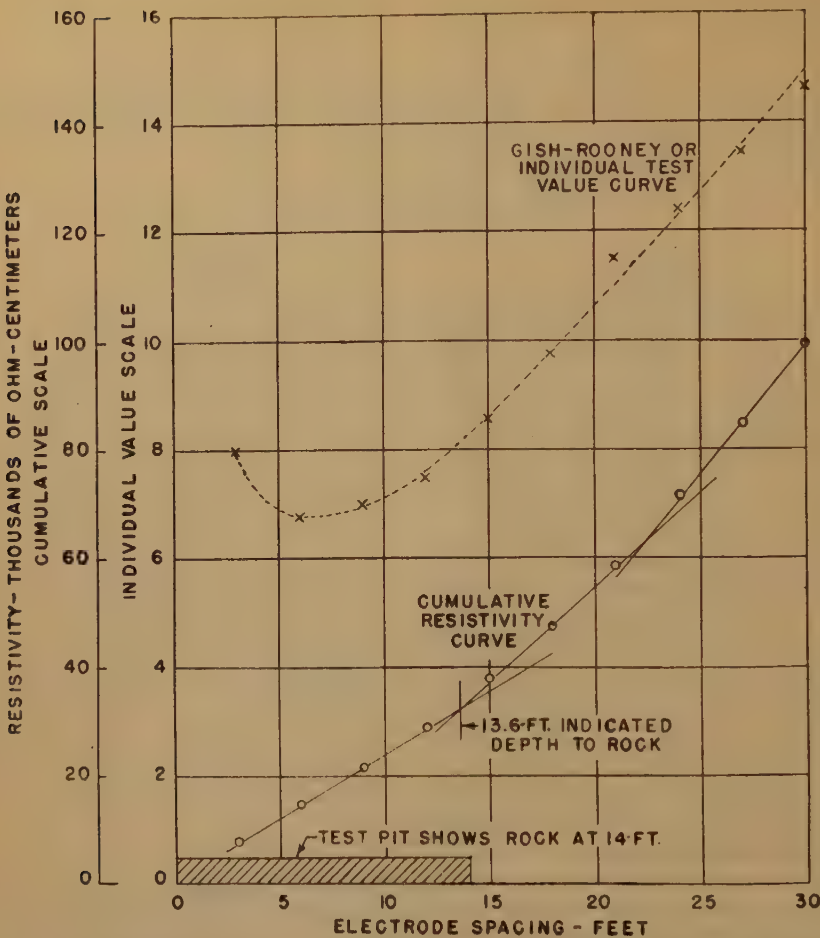

FIG. 1.—TYPICAL RESISTIVITY DATA AND METHOD OF ANALYSIS USING THE CUMULATIVE RESISTIVITY CURVE.

TABLE 1.—*Resistivity Depth Test Data Used in Figure 1*

Electrode Spacing, Ft.	Apparent Resistivity, Ohm-cm.	Cumulative Resistivity, Ohm-cm.	Remarks
3	8,000	8,000	Test pit shows clay to depth of 14.0 ft. underlain by hard rock
6	6,800	14,800	
9	7,050	21,850	
12	7,510	29,360	
15	8,600	37,960	
18	9,800	47,760	
21	11,550	59,310	
24	12,430	71,740	
27	13,500	85,240	
30	14,650	99,890	

the resistivity test in the field of highway construction. Prior to 1940 the empirical relation proposed by Gish and Rooney[2] was generally used for the study of the field data. In this method of analysis, the apparent resistivities measured for a succession of gradually increased electrode spacings are plotted as ordinates and the corresponding electrode spacings as abscissas. An empirical relation appears to exist, in which the so-called "effective depth" of current flow approximates the value of the electrode spacing used. If, within this "effective depth," an underlying formation with a specific resistance materially different from that of the surface layer is encountered, an inflection will presumably be found in the apparent resistivity-electrode spacing curve. Gish and Rooney found that where such an inflection appeared the value of the electrode spacing at the point of inflection could be interpreted as the approximate thickness of the surface layer. Where a low-resistivity material is underlain by one of a higher resistivity a U-shaped curve is often obtained and in such cases the electrode spacing for the low point of the curve is usually interpreted as indicating the depth to the underlying material.

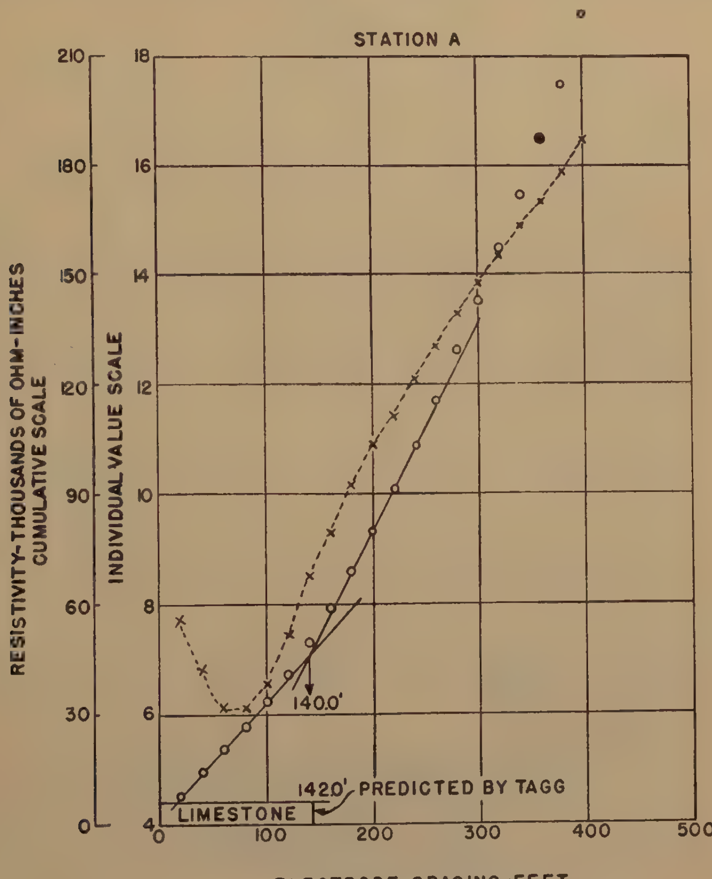

FIG. 2.—REPRODUCTION OF TAGG'S CURVE FOR STATION A.[3]

In many instances, in connection with shallow work abrupt breaks in the curves

for apparent resistivity vs. electrode spacing have been found, which, when interpreted in this manner, give a reasonably accurate indication of the position

The following discussion relates to an empirical method of analysis that has been developed in connection with the resistivity research of the Public Roads

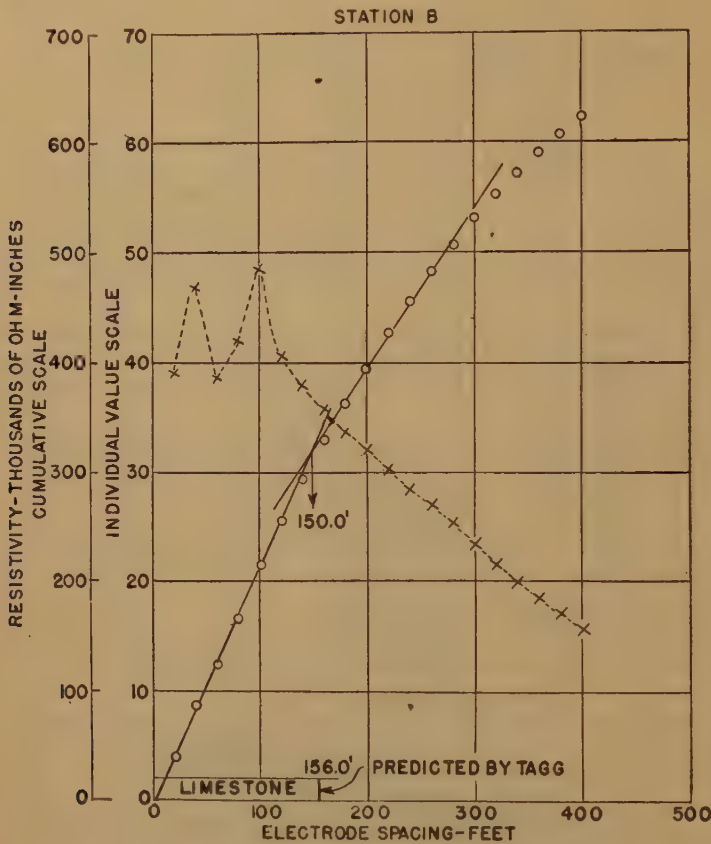

FIG. 3.—REPRODUCTION OF TAGG'S CURVE FOR STATION B.[8]

of the interface between the surface materials and the underlying material in simple two-layer formations. There are other instances, however, in which resistivity depth tests in two-layer or multilayer formations yield apparent resistivity-depth curves that are smoothly rounded, with no marked inflections or other indications of the position of the various strata. For such curves no satisfactory empirical method of analysis is available and such theoretical methods as have been proposed are both uncertain and time consuming.

Administration. When applied to data obtained both by this agency and by others, over a wide range of field conditions, it seems to offer definitely better correlations than other methods where the test data are of the type described above.

PROPOSED METHOD OF ANALYSIS

In the proposed method of analysis the data are obtained in the field using the Wenner[1] four-electrode configuration and a conventional Gish-Rooney curve (apparent resistivity vs. electrode spacing) is

prepared. The Gish-Rooney curve is used for whatever indication it may give of subsurface conditions at the point of test. The data in the curve are replotted on the shallow work, is chosen arbitrarily and the electrode spacing is then increased regularly by increments of 3 ft. for each successive determination. The initial value

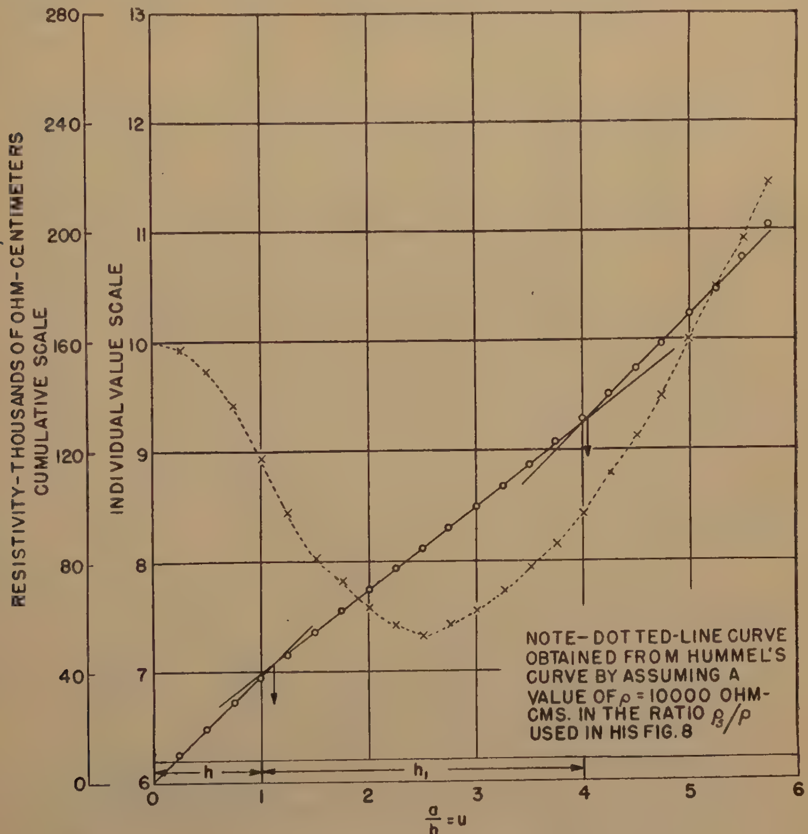

FIG. 4.—HUMMEL'S CURVE OF APPARENT RESISTIVITY FOR CASE OF $h_1 = 3h$ AND RATIO $\rho_0 : \rho : \rho_1 : \rho_2 = \infty : 1 : 0.5 : \infty$ (HIS FIG. 8).[4]

same sheet in the form of a cumulative resistivity-electrode spacing curve. By reason of a greatly reduced ordinate scale and the effect of successive summations of individual resistivity values, this plotting of the data tends to minimize the effect of any single resistivity value and thus eliminate purely local effects caused by surface anomalies or any peculiarity of a particular setting of the electrodes.

In obtaining the field data for plotting in this manner, an initial electrode spacing of some convenient value, say 3 ft. for of apparent resistivity is plotted as the initial ordinate of the cumulative curve. Each subsequent value of apparent resistivity is added to the sum of all preceding resistivity values and each total thus obtained is plotted as the ordinate of another point in the cumulative curve. By using regularly increased electrode spacings (for example, 3 ft., 6 ft., 9 ft., etc.) it would appear that a substantially straight line with a given slope should be obtained as long as the "effective depth" of current flow remains primarily within the surface

layer and this layer consists of a relatively homogeneous material. In practice, however, where the surface material is relatively shallow and the soil layer is not corresponding approximately to the depth of the surface layer the plotted cumulative curve usually tends to change direction, the new slope depending upon the relative

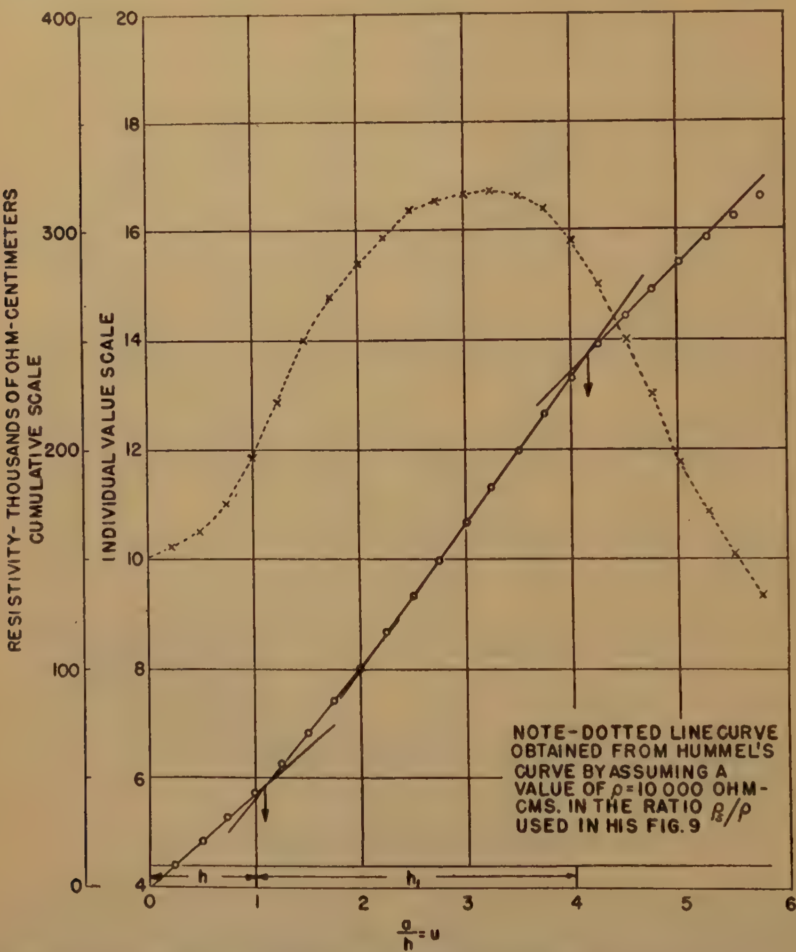

FIG. 5.—HUMMEL'S CURVE OF APPARENT RESISTIVITY FOR THE CASE OF $h_1 = 3h$ AND RATIO $\rho_0:\rho:\rho_1:\rho_2 = \infty:1:3:0$ (HIS FIG. 9).[4]

perfectly homogeneous the plotted data frequently are in the form of a generally smooth curve of gentle curvature rather than in a straight line. Probably this is due to gradual changes of resistivity with depth and with soil variation.

It has been found that as the electrode spacing approaches and passes a value resistivities of the two layers of material. From the electrical principles involved, this slope should increase if the lower formation possesses a higher resistivity than the surface layer, and, conversely, should decrease if the underlying formation is the more conductive. It has been found that lines drawn tangent to the cumulative

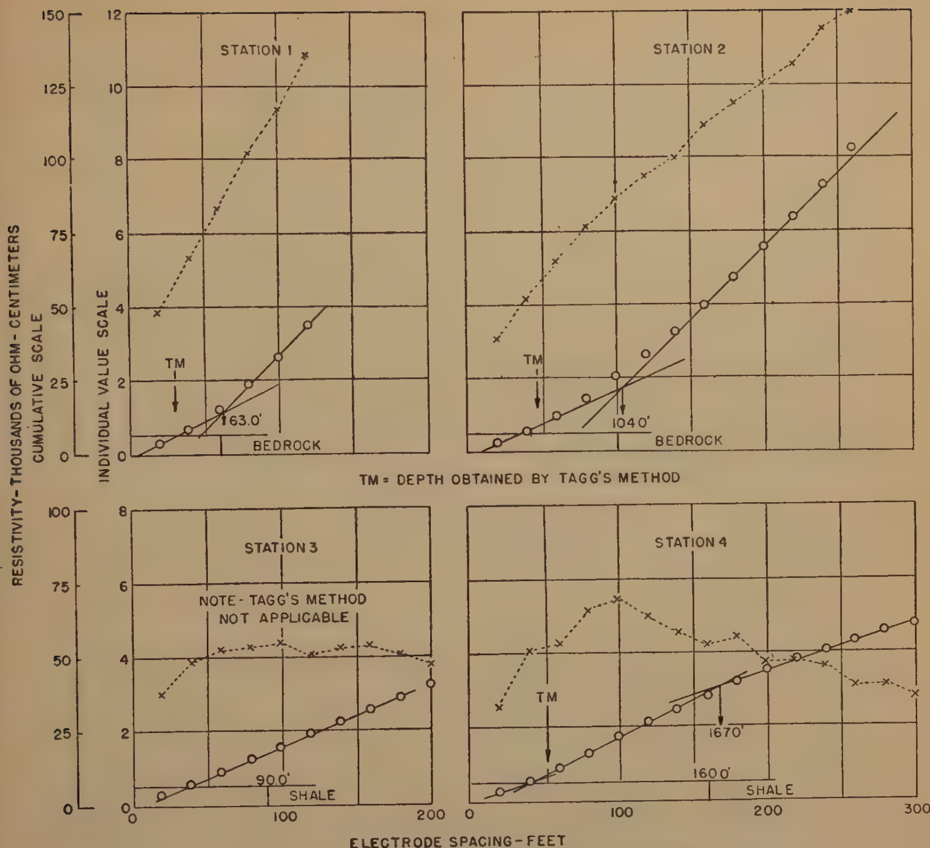

FIG. 6.—CURVES PLOTTED FROM FIELD DATA OF HUBBERT'S TABLE 1.[5]

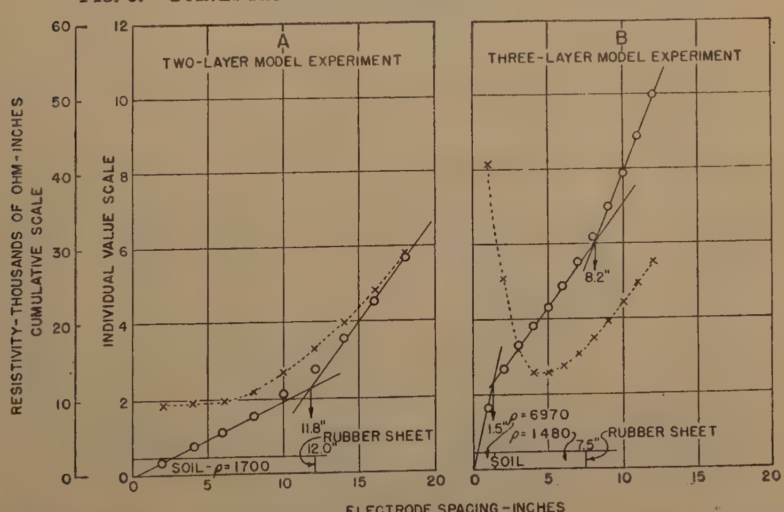

FIG. 7.—CUMULATIVE-RESISTIVITY-CURVE METHOD OF ANALYSIS APPLIED TO MODEL EXPERIMENT DATA OBTAINED BY R. J. WATSON (HIS FIGS. 20 AND 21).[6]

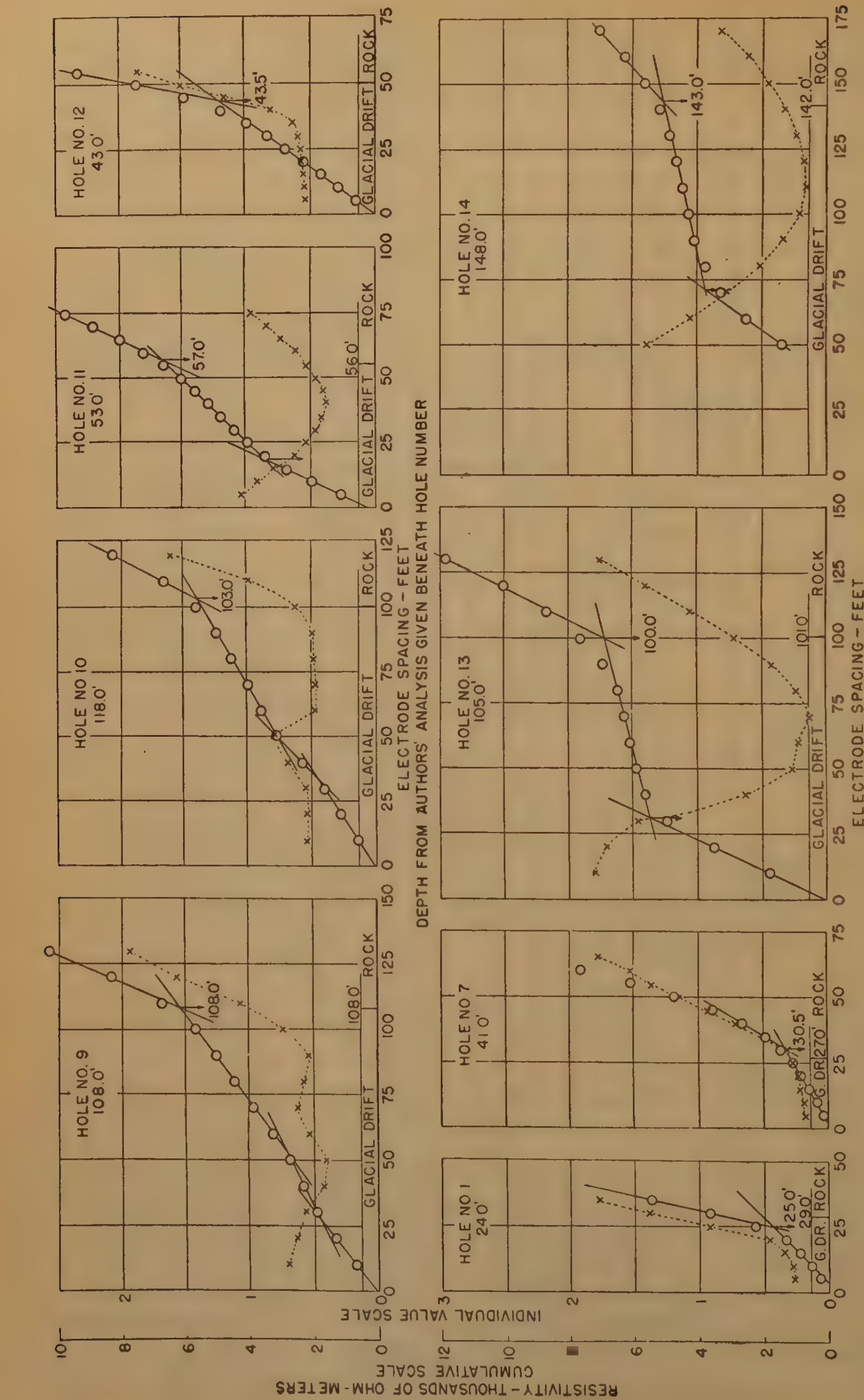

FIG. 8.—REPRODUCTION OF CROSBY AND LEONARDON'S CURVES (FIGS. 6–13).[7]

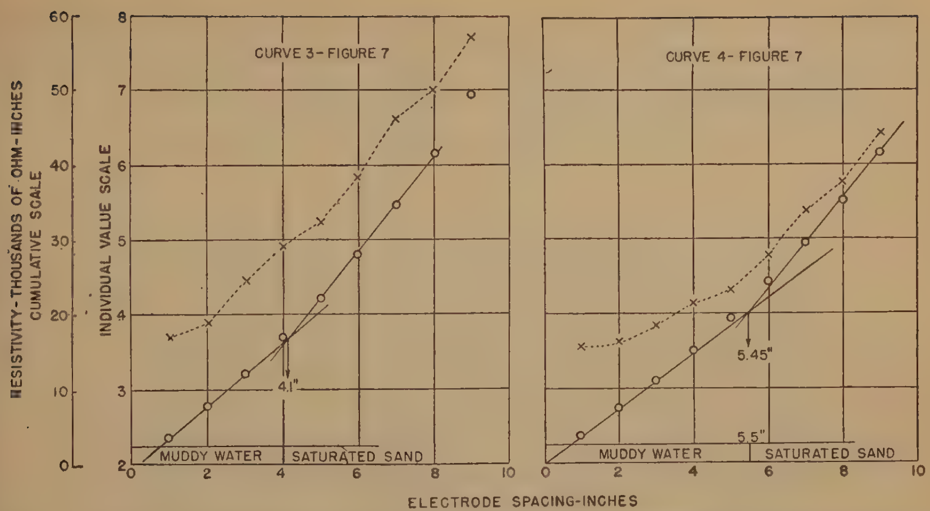

FIG. 9.—CUMULATIVE-RESISTIVITY-CURVE METHOD OF ANALYSIS APPLIED TO MODEL EXPERIMENT DATA OBTAINED BY T. A. MANHART.[8]

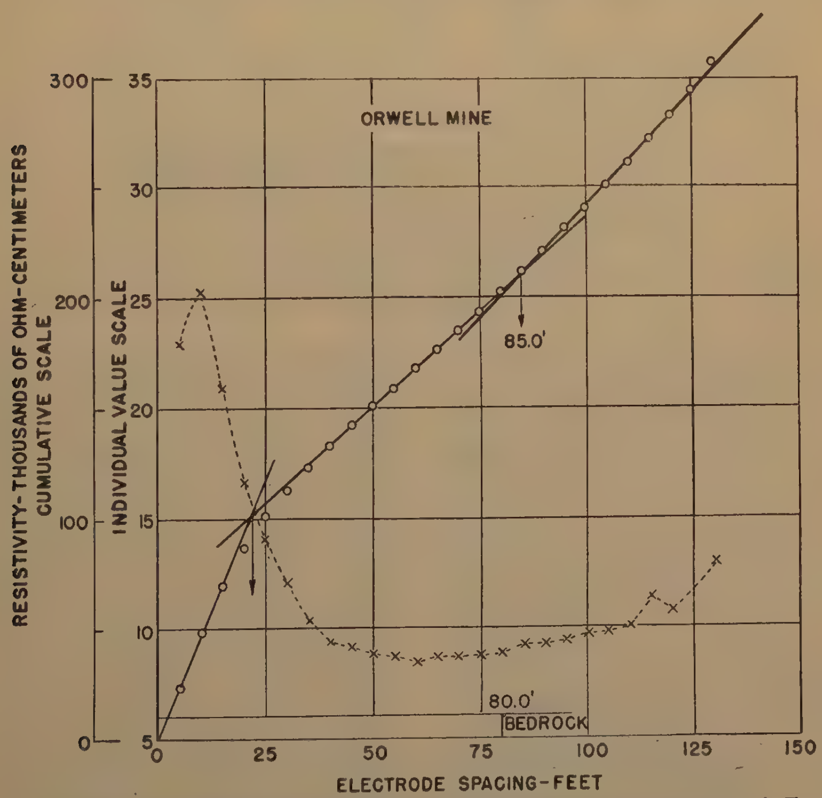

FIG. 10.—CUMULATIVE-RESISTIVITY-CURVE METHOD OF ANALYSIS APPLIED TO ROMAN'S FIGURE 9.[9]

curve and intersecting in the region where the change in slope occurs will give a good approximation of the depth to the interface between the two materials if the point of method of presenting the data is employed in each of the subsequent figures and for simplicity the identification of the curves is not repeated.

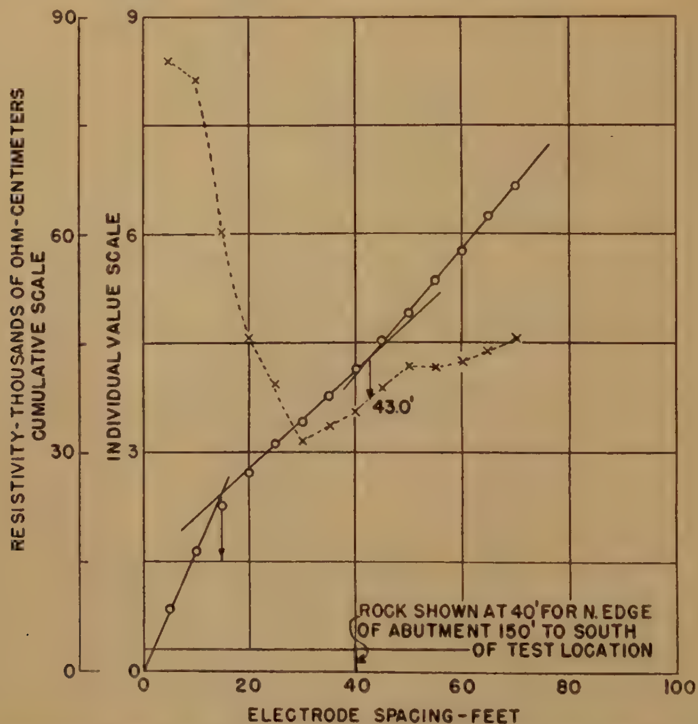

FIG. 11.—RESISTIVITY TEST NEAR WEST ABUTMENT OF ARLINGTON MEMORIAL BRIDGE, WASHINGTON, D. C.

intersection of the tangents is projected to the horizontal or depth axis. Fig. 1 illustrates the method applied to a typical case; the data used in plotting the curves are given in Table 1. The values of electrode spacing and of apparent resistivity in columns 1 and 2, respectively, were obtained in field tests in the vicinity of Washington, D. C., where there existed a simple two-layer formation consisting of clay underlain by rock.

In Fig. 1 the Gish-Rooney or individual test-value curve is shown by crosses connected by a dashed-line curve and the cumulative resistivity curve by plotted circles. For clarity the curve connecting the circles has been omitted. This same

Referring to Fig. 1, the presence of the high-resistance rock formation at the relatively shallow depth of 14 ft. affects strongly the measured apparent resistivity beyond an electrode spacing of about 10 ft., and for this reason the plotted values of cumulative resistivity continue to show a rather marked degree of curvature beyond what might be termed the "critical point" in the curve. The trend of the Gish-Rooney or individual test-value curve is used to indicate the probable "critical point," which in this curve appears to be at an electrode spacing of 10 to 12 ft. Guided by the indications of this curve and such correlating data as may be available from test pits or drill

holes in the general area, the additional tangent intersections beyond the "critical point" may or may not be disregarded.

Admittedly, this is empirical in every sense but the results that have been obtained in the analysis of data from many tests under various field conditions have been encouraging. In addition to the use of this method of analysis for data obtained in field tests in connection with the work of the Public Roads Administration, the literature has been reviewed and resistivity curves presented by various authors have been replotted and analyzed by the method wherever the necessary depth data were given. The results obtained appear to substantiate the conclusions reached in analyzing the data obtained in the field.

Fig. 2 shows Tagg's[3] "classical" curve for his station A, representing typical field data to which he applied his method of analysis, together with the points that result when the data are replotted in the manner previously described. Fig. 3 shows a similar treatment of Tagg's station B.

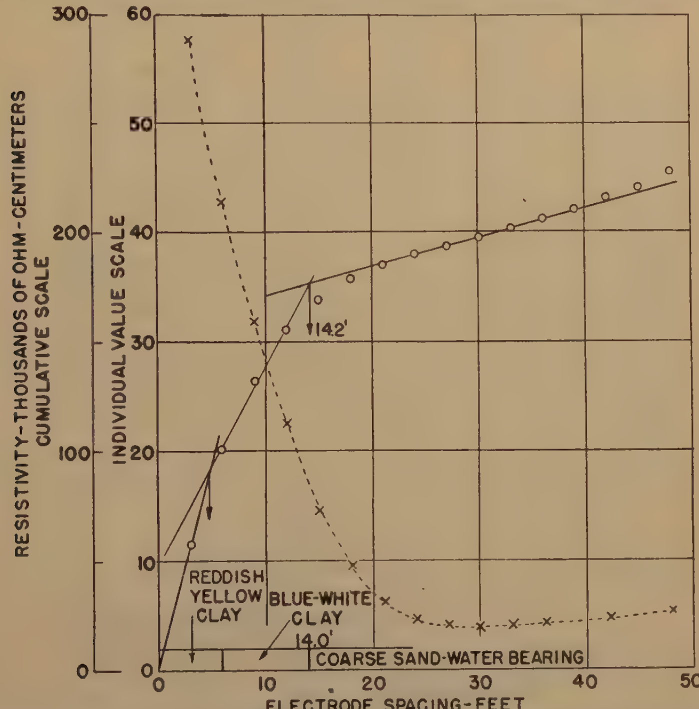

FIG. 12.—RESISTIVITY TEST AT LOCATION OF PROPOSED RAILWAY UNDERPASS NEAR PETERSBURG, VIRGINIA.

The cumulative values in Figs. 2 and 3 indicate depths that closely approximate those obtained by Tagg with a rather laborious method of analysis. In connection with these curves and others that are to be presented, it should be pointed out that frequently it is rather difficult to read accurately values of the coordinates from the necessarily small figures found in the published papers when taking off data for replotting.

Figs. 4 and 5 show Hummel's[4] curves of apparent resistivity for two theoretical cases in which two surface layers of differing resistivity and thickness are underlain by, in one case, a layer having an infinitely high resistivity and in the other a layer

having an infinitely high conductivity, as shown in his Figs. 8 and 9. The ordinate v of Hummel's Figs. 8 and 9 is given as the ratio ρ_a/ρ in which ρ is the true resistivity three-layer condition was involved in both instances.

The curves shown in Fig. 6 were plotted from data presented in Table 1 of a paper

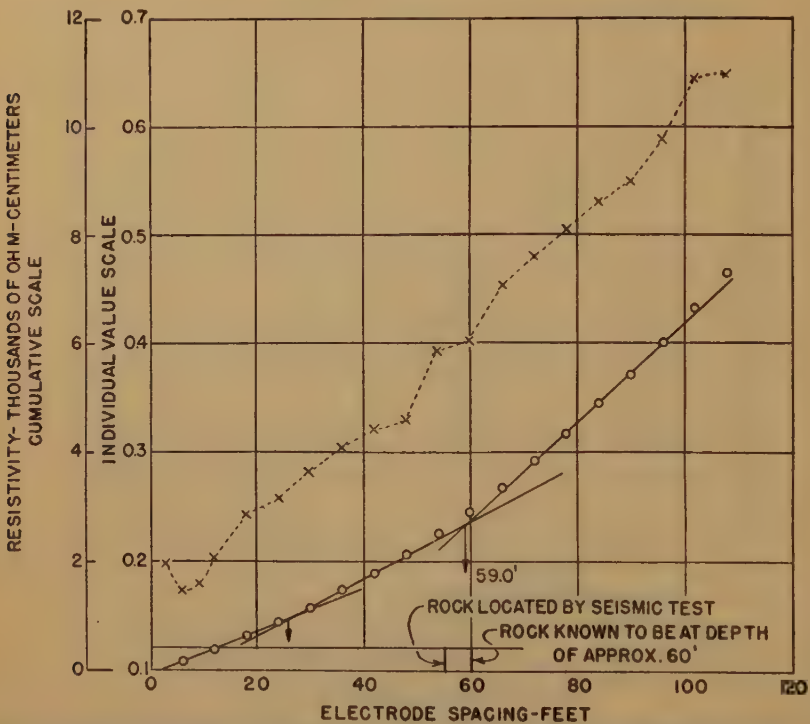

FIG. 13.—RESISTIVITY DEPTH TEST IN SALT MARSH NEAR HAMPTON, NEW HAMPSHIRE.

of the upper layer of the ground and ρ_a is the average or apparent resistivity resulting from the influence of the underlying layers on the values of resistivity as measured at the ground surface. In plotting the dotted-line curves in Figs. 4 and 5, a value of 10,000 ohm-cm. was assumed for ρ and applied to the ratios ρ_a/ρ taken from Hummel's curves. This resulted in conventional curves for apparent resistivity vs. electrode spacing, from which the data for plotting the cumulative curves were obtained. The position of the interfaces as determined from the cumulative curve appears to agree with that assumed in the theoretical treatment rather closely despite the fact that a by Hubbert.[5] The data for his stations 1, 2 and 4 check the known conditions reasonably well when plotted using the cumulative value of resistivity. As stated by the author, Tagg's method of analysis, although giving good intersection zones for the three sets of curves plotted for stations 1, 2 and 4 gives depth indications that are in error by 50, 54 and 70 per cent for the respective stations. The individual test value or Gish-Rooney curves for these stations were of little value in determining the depths involved. The data for station 3 apparently cannot be interpreted by any known method.

In Fig. 7 are data from a paper by Watson,[6] in which curves obtained from

model experiments are described. In the experiments he performed a carefully prepared sandy shale was screened and mixed with different percentages of moisture to form surface layers having different resistivities. A rubber sheet was placed under the surface layer to simulate a bottom layer having infinite resistivity. In both cases compared the cumulative curve indicates rather accurately the location of the buried rubber sheet as well as the interface between layers of soil of different resistivity.

Fig. 8 contains reproductions of several curves published by Crosby and Leonardon.[7] The depth to rock as predicted by these authors is noted on each of the graphs in Fig. 8 and the depth to rock as obtained by drilling is shown along the lower edge. With three exceptions, the cumulative-curve method of analysis checked the actual conditions existing beneath the surface within about 3 per cent. The average error for all curves was 5.8 per cent.

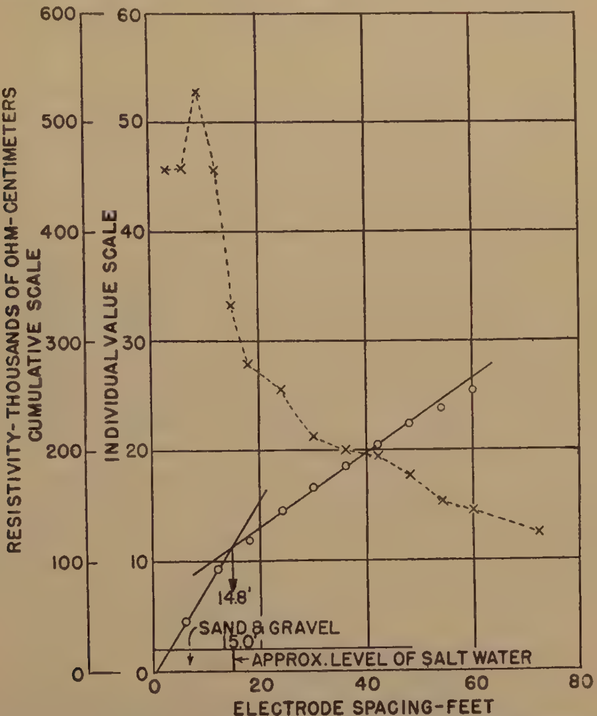

FIG. 14.—RESISTIVITY DEPTH TEST ON SAND AND GRAVEL FILL APPROXIMATELY 15 FEET ABOVE SEA LEVEL NEAR HAMPTON, NEW HAMPSHIRE.

No data were included in Crosby and Leonardon's paper relative to variations in the material classed as glacial till, which overlay the rock. It is possible that the presence of a water table is responsible for the breaks in some of the cumulative resistivity curves at depths less than those given for the rock surface.

Fig. 9 reproduces curves 3 and 4 of Fig. 7 of a paper by Manhart.[8] He reported on model tank experiments in which he made numerous tests under laboratory-controlled conditions. The two curves shown in the figure were obtained when using a surface layer of muddy water underlain by saturated sand. The typically smooth curves obtained from Manhart's

experiments lend themselves well to a solution by the cumulative-curve method of analysis. Of the many curves presented by Manhart, 13 were analyzed by the curve of apparent resistivity vs. electrode spacing and also in the form of the corresponding cumulative curve. ρ_a, the apparent resistivity, was assumed to be given in

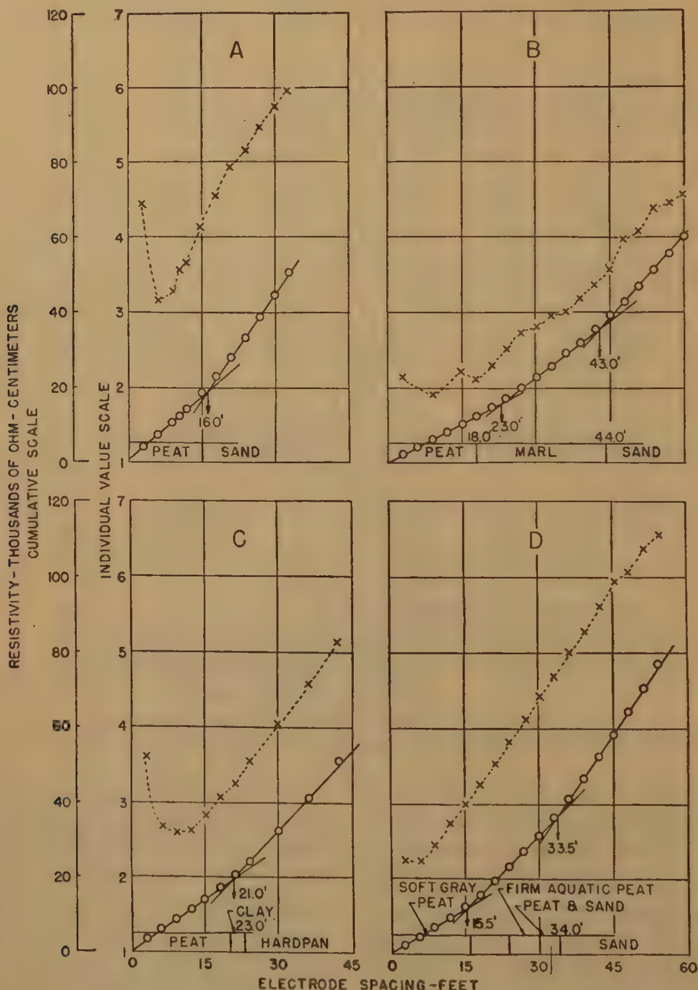

FIG. 15.—RESISTIVITY DEPTH TESTS OVER PEAT-BOG FORMATIONS

proposed method, four two-layer and nine three-layer curves comprising 22 possible depth determinations, and in only two or three cases were the conditions indicated by the analysis materially different from those established in the laboratory.

In Fig. 10 a curve given by Roman[9] in his Fig. 9 has been replotted as a normal ohm-cm. Roman suggests that further theoretical studies are required to make possible the interpretation of such curves. Although use of the original apparent-resistivity and electrode-spacing data would have given a more accurate curve for use in the empirical analysis that is proposed, the data shown in Fig. 10 indicate that

the cumulative-curve method of analysis has given a reasonably accurate depth determination. The depth of 80 ft. to bedrock was given in the discussion that stated previously, both the Gish-Rooney and the cumulative curves are used in interpreting the data from a particular test. The general shape of the Gish-Rooney

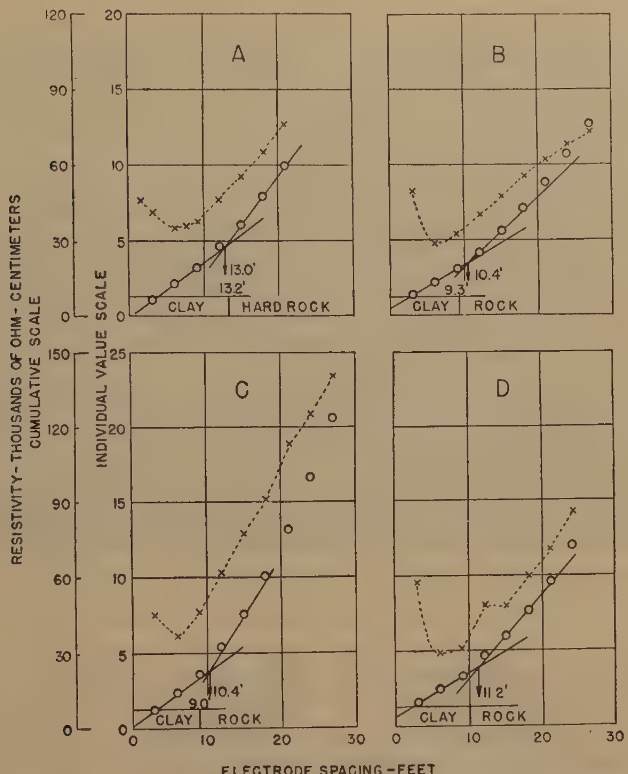

FIG. 16.—EMPIRICAL METHOD OF ANALYSIS APPLIED TO RESISTIVITY CURVES FOR A CLAY STRATUM UNDERLAIN BY ROCK IN THE VICINITY OF WASHINGTON, D. C.

followed the presentation of Roman's paper. Mention also was made in the discussion of the presence of swampy materials underlain by hardpan which overlay the rock at the test location. The change indicated in the cumulative curve at a depth of approximately 22 ft. may be at the boundary between these two surface materials.

Many other published data have been replotted and analyzed by the cumulative-curve method, with about the same general degree of success. There are border-line conditions of test which do not lend themselves to an analysis by this method. As curve serves to indicate the probable ground conditions, whether two-layer or more, and it may also give some clue to the approximate depth of the surface layers.

Field Tests Conducted by the Public Roads Administration

The results of tests conducted by the Public Roads Administration that involve a variety of surface and subsurface conditions encountered in the vicinity of Washington, D. C., and in New Hampshire are shown in Figs. 11 to 14. The curve in Fig. 11 was obtained near the west abut-

ment of the Arlington Memorial Bridge across the Potomac River at Washington, D. C. At this location a few feet of earth fill overlay soft mud, which in turn was underlain by a rock formation. The depth of 43 ft. to rock indicated by the cumulative curve is in reasonable agreement with the depth of 40 ft. found by drilling at the abutment location about 150 ft. to the south. The change shown by the cumulative curve at a depth of about 15 ft. was probably where the fill material merged with the underlying mud.

FIG. 17.—IRREGULAR SURFACE OF ROCK FORMATION THAT WAS INVOLVED IN THE RESISTIVITY TESTS.

Fig. 12 shows data for a test where heavy clay was underlain by coarse, water-bearing sand at a depth of 14.0 ft. The relatively smooth individual value or Gish-Rooney curve shows no indication of the sand stratum at that depth but it is located at 14.2 ft. on the cumulative resistivity curve.

Fig. 13 contains the resistivity curve obtained at a location in the salt marshes near Hampton, N. H., where rock was known to be at a depth of approximately 60 ft. The Gish-Rooney curve shows an increased upward trend at an electrode spacing of 48 ft. The cumulative curve checked the known depth and the depth indicated by refraction seismic tests made near by within about 1.7 and 6.9 per cent, respectively. In the absence of previous knowledge of the general nature of the subsurface formation, it may be necessary to put down one or two drill holes to establish the significance of data that show several changes in direction or "breaks" in the cumulative curve.

In Fig. 14 are shown the results of tests made on a sand and gravel fill near the sea and about 15 ft. above sea level at Hampton, N. H. The cumulative curve indicates a low-resistivity medium such as salt water at about 15.0 feet.

Curves representative of tests made with the resistivity apparatus over peat bogs are shown in Fig. 15. In this series of tests the cumulative curve proved to be a satisfactory means of analyzing the data obtained. These tests are of interest because it seemed probable that the peat and marl formations overlying the sand or hardpan usually comprising the bottom formations of the bogs would approach the uniform

layers of homogeneous materials assumed in theory, thus presenting conditions that would be particularly suitable for a satisfactory analysis by the resistivity method.

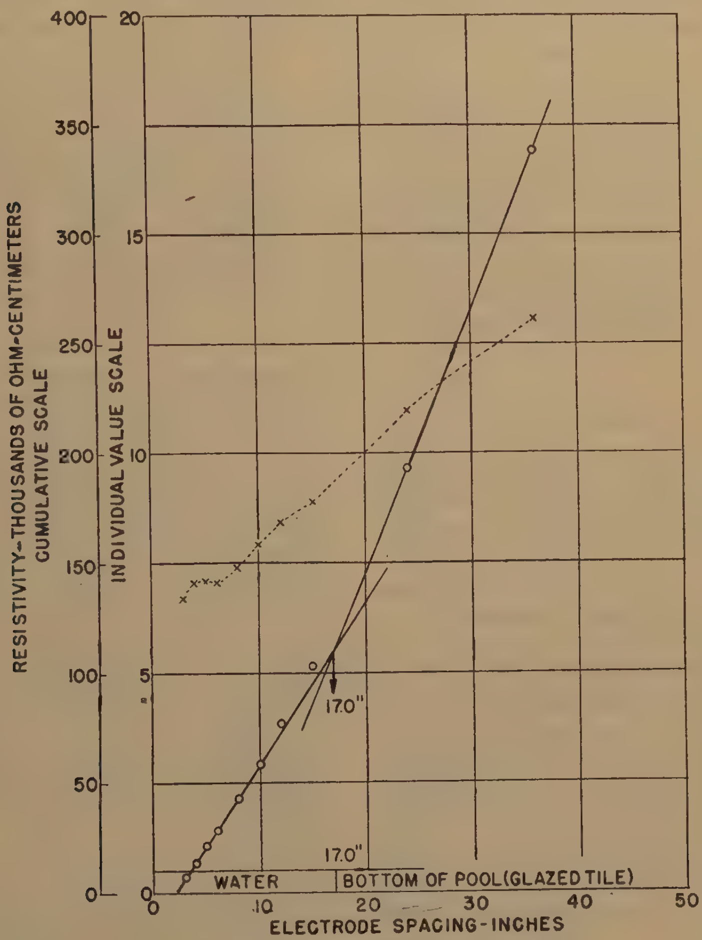

Fig. 18.—Results of tests in tiled pool.

Furthermore, it was relatively simple to check directly the indications of the resistivity tests by means of rod soundings with equipment capable of taking samples at any desired depth.

Fig. 16 shows data from an extensive resistivity survey project completed in the spring of 1942 in the vicinity of Washington, D. C. Based upon some 475 to 500 depth tests and about 10.5 miles of "resistivity traverse" covering an area of about 150 acres, a map was prepared showing subsurface rock elevations by means of rock-surface contours. Numerous check borings, with post-hole auger equipment, and direct observations in excavations made subsequent to the preparation of this map, indicated an average accuracy of 1 to 2 ft. for the rock contours as established. The depth of the surface clay varied from about 4 ft. to 30 ft. The underlying rock was a granite formation of quite irregular contour, as shown in Fig. 17. It was found that a difference of 6 ft.

vertically could be encountered by a post-hole auger in as little as 6 ft. horizontally in places where such irregularities were the more pronounced. Under such conditions the resistivity test should offer more dependable over-all depth values than a limited number of individual borings.

The results of tests conducted in the tiled pool in the plaza of the National Academy of Science, Washington, D. C., are given in Fig. 18. The Gish-Rooney method of plotting the data showed no indication of the depth of the water in the pool, whereas an analysis with the cumulative curve shows a remarkable correlation with the measured depth of water, 17 inches.

Summary

The cumulative-resistivity-curve method of analysis offers a simple and rapid means of determining the depth to an underlying formation in cases that show no definite indication of its presence in the apparent-resistivity-electrode-spacing curve.

Although best suited to shallow two-layer formations, the cumulative curve has been applied with good results to data from relatively deep tests and for both two-layer and three-layer formations. It has proved to be particularly useful where rapid reconnaissance surveys are being made over relatively large areas and where more detailed and time-consuming methods of analysis are not justified economically. This method of analysis is intended to augment and supplement other methods in current use rather than to displace them.

References

1. F. C. Wenner: A Method of Measuring Earth Resistivity. Nat. Bur. Stds. *Sci. Paper* 258 (1915).
2. O. H. Gish and W. T. Rooney: Measurement of Resistivity of Large Masses of Undisturbed Earth. *Terrestrial Magnetism and Atmospheric Electricity* (1925) **30**, 161.
3. G. F. Tagg: Interpretation of Earth-resistivity Measurements. *Trans.* A.I.M.E. (1934) **110**, 135.
4. J. N. Hummel: A Theoretical Study of Apparent Resistivity in Surface Potential Methods. *Trans.* A.I.M.E. (1932) **97**, 392.
5. M. K. Hubbert: Results of Earth-resistivity Survey on Various Geologic Structures in Illinois. *Trans.* A.I.M.E. (1934) **110**, 9.
6. R. J. Watson: A Contribution to the Theory of the Interpretation of Resistivity Measurements Obtained from Surface Potential Observations. *Trans.* A.I.M.E. (1934) **110**, 201.
7. I. B. Crosby and E. G. Leonardon: Electrical Prospecting Applied to Foundation Problems. *Trans.* A.I.M.E. (1929) **81**, 199.
8. T. A. Manhart: Model Tank Experiments and Methods for Interpretation of Resistivity Curves. Colorado School of Mines *Quarterly* (Jan. 1937) **32**.
9. I. Roman: Some Interpretations of Earth-resistivity Data. *Trans.* A.I.M.E. (1934) **110**, 183.

DISCUSSION

(*L. W. Blau presiding*)

S. W. Wilcox.*—Several old earth-resistivity depth profiles were replotted using the accumulative method suggested by Mr. Moore, with results inconsistent with my original interpretations. However, minor irregularities in the conventional curves were smoothed out and definite changes in slope observed on the accumulative curves might have correlative value. Unfortunately, the subsurface control at the depth points was incomplete and the new interpretation cannot be adequately checked against the logs. For the smooth apparent-resistivity electrode-spacing curves replotted by the accumulative method, unique inflection points were obtained, which give something tangible for empirical interpretation.

As Mr. Moore points out in his paper, there is apparently no scientific basis for the naive interpretation of the empiricists; however, their method is remarkably useful for many simple earth-resistivity investigations. Mr. Moore's paper is a definite contribution to shallow earth-resistivity studies and points out a useful technique—as long as the operator carefully checks his interpretation against subsurface control.

I. Roman†—This paper presents a clear, direct attack on a problem under study for

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* Seismograph Service Corporation, Tulsa, Oklahoma.

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about two decades. The method is a single example of empirical attacks on the interpretation of earth-resistivity measurements. Such methods have been in use and are proving useful, but as they have not been published, only confidential information is available concerning them.

As the present speaker sees the issue between theoretical and empirical methods, the distinction is superficial rather than real. Each furnishes a working hypothesis for obtaining results in special applications; each is based on assumptions verified by experience. A method is empirical if the author gathers his own experience, and theoretical if he uses the collected experiences of his predecessors. Each method leads to success in some instances and fails in others. The practical geophysicist is interested in predicting substructures from data. Any available method is satisfactory if it leads to a suitable interpretation. Experience and judgment must determine the methods to be tried, and usually a combination of several methods is preferable to any single method. Although the speaker leans strongly to theoretical analyses, he is not opposed to empirical attacks by those interested in them. Each interpreter must decide on his own tools, and his success reflects the wisdom of his choices. No apology is needed for the selections.

Theoretical analyses have proved very useful and satisfactory. When a theoretical curve can be made to fit an observed curve, the assumed structural features may be considered highly probable—correct, as the term is usually used. If no theoretical curve will reproduce the curve of observations, the interpreter must resort to some other method until the theory can be extended to cover the specific data. In the present problem, the theoretical attack is very complicated. The theoretical solutions offered to the present time can be applied only to very simple structures. Until the theory is simplified in some manner, most interpreters will need to utilize empirical methods.

The present paper represents an "integration" method. In general, an integral curve smooths out observations and emphasizes trends because it requires a reduced ordinate scale and minor fluctuations are relatively smaller. Expressed in another manner, the integral curve consists of more nearly straight lines, if the observation curves are approximately horizontal or of nearly uniform slope. Hence, linearity is often suggested in the integral curve, where it would be missed in the observation curves. This has definite advantages.

In the other direction, difference curves, corresponding to derivatives, emphasize individual observations. They are often useful in detecting anomalous observations, whether due to instrumental errors or important characteristics of the field being measured. On difference curves, the location of the discordant observation is important.

In some empirical methods combinations of the integral and difference values are used. The specific combination is usually determined by the intuitive reaction of the interpreter and the degree of success he has had with his choice.

The present method, along with integration methods in general, has one important objection. It is extremely sensitive to the personal equation of the interpreter. Slight variations in the "lines of best fit" may make a considerable difference in the intersection of two lines. While such variations in interpretation may be unavoidable, overlooking this detail may give the interpreter a false sense of security and lead him into unwarranted conclusions in untested area. The method should be used with caution, but this is not a reason for refusing to use it at all.

The author is to be complimented on presenting the results of his empirical studies. Perhaps this paper will open the way for publication of other empirical methods. How many are in use is not known, but probably there are several dozens of them in use in this country alone.

W. T. Holser.*—This paper is interesting not only for the data and method it presents but because it brings once again to the fore the old debate between the theorists and the "practical men." There is much to be said for either an empirical or a theoretical solution to any problem, but the final, fully satisfactory answer can only be either an experimental verification of a theory, or a general law inductively reasoned from the known data. One

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thing that can be said for such a final solution is that theory or law allows more rational use of the empirical rule and a surer knowledge of its limitations. For this reason I believe an attempt should be made to elucidate the theory behind this and other empirical rules.

An analytical examination of Mr. Moore's method reveals several things. In the first place it is obvious that his curve represents an integration of the Gish-Rooney curve (taken incrementally); or, conversely, the slope of the Moore curve at any point is the ordinate of the corresponding point on the Gish-Rooney curve. A straight line on a Moore curve therefore represents a constant ordinate on the Gish-Rooney curve; i.e., a horizontal straight line. Therefore, in what would presumably be an ideal Moore curve, a series of connected straight lines of different slopes, the corresponding Gish-Rooney curve is a series of steps. The point of discontinuity, or step, is interpreted as the boundary depth, which significantly parallels the old "potential bowl" theory.[10] The limitations of this rule are well known, especially in cases of large resistivity ratios in the two layers. Inasmuch as the Moore method has the same inherent errors as the potential bowl theory, it ought to be used with the same caution.

In this discussion it was assumed that Mr. Moore was able to draw straight lines passing through all of the summed points. In any practical case, of course, this will not be possible, because of differential and random variations of resistivity with depth, and multiple path effects. We must therefore find an *average slope* over a certain range, corresponding to an *average ordinate* of the Gish-Rooney curve. What is done actually is to draw lines tangent to the curve at points of inflection or in regions of constant slope. Then the point of change of mean resistivity (corresponding to the "potential bowl depth") will be indicated by an intersection of the tangent lines. The problem of just where to draw this tangent is a ticklish one, and Mr. Moore only says, "tangent to the cumulative curve and intersecting in the region where the change in slope occurs . . . " As it is the region of change of slope we are trying to find by drawing the tangents. this is no help. In this connection it would be well to ascertain when a tangent *cannot* be drawn (and the method therefore is inapplicable). Obviously, if a portion of the Moore curve is a line of constantly changing slope (a parabola), any number of different tangents might be drawn to it. Any part of a Gish-Rooney curve that is a *straight line* (except horizontal) will give a constantly changing slope, therefore tangents drawn in such portions can only be misleading. Several examples are apparent in the paper:

Fig. 3, beyond 120 ft (tangent could equally well have been drawn to intersect anywhere from there to 300 ft.).

Fig. 6, stations 1 and 2.

Fig. 7, two-layer model, beyond 10.5 feet.

Fig. 8. hole No. 12 beyond 35 ft.; hole No 1, beyond 20 ft.

Fig. 12, below 15 ft. (It is to be noted here that the origin is used as a valid point, whereas in other curves, notably Fig. 8, hole No. 14, it is disregarded.)

Fig. 15*D*.

Fig. 16*A*, *B*, and *C*.

Fig. 18 (there is a beautiful intersection at 11 in.).

This particular treatment of experimental data—namely, the integration and "drawing of average tangent"—to obtain the mean value of a curve is unique from the standpoint of the usual methods of statistical analysis. This paper demonstrates its utility, however, as an examination of most of the original Gish-Rooney curves does not reveal obvious "grouping" of values, which are easily seen as average slopes when the summation curves are drawn. The method is a very real help both in averaging out local anomalies and (in a more restricted sense) in calculating the mean constant effect of a varying quantity. By first applying the "straight-line test" to the original curve, and bearing in mind that the loss of resolution inherent in this type of construction necessitates a more careful drawing of curves, the method can be employed to advantage in this, as well as other, statistical problems.

C. A. HEILAND.*—Mr. Moore's paper brings to mind some work we have done

[10] A. S. Eve and D. A. Keys: Applied Geophysics in the Search for Minerals, 95–97. 1938, Cambridge University Press.

* Heiland Research Corporation, Denver, Colo., and Professor of Geophysics, Colorado School of Mines, Golden, Colorado.

in connection with the design and construction of a resistance gradiometer, which was concerned with the integration and differentiation of apparent resistivity depth curves. Our results, reported briefly herein, are at variance with much of the material and conclusions presented by Mr. Moore.

Essentially, Mr. Moore's method of analysis involves the graphical integration of the apparent resistivity curve. On the basis of the assumption that the integral curve consists of straight-line portions, the author aims to prove that breaks between these portions occur at electrode separations corresponding to the depths of the interfaces involved. At first glance this method is deceivingly simple; further investigation shows, however, that: (1) the basic assumption of straight lines is not justified, and (2) that in practice the location of the intersections may be so arbitrary as to seriously limit the usefulness of a straight-line approximation.

Mr. Moore himself recognizes these facts when he says that "the plotted data frequently will be in the form of a generally smooth curve of gentle curvature rather than the straight line." His conclusions as to the cause of this situation are in error, however. He says that in the integrated curve "a substantially straight line with a given slope should be obtained so long as the effective depth of current flow remains primarily within the surface layer and this layer consists of a relatively homogeneous material. In practice, however, where . . . the soil layer is not perfectly homogeneous the plotted data frequently will be in the form of a generally smooth curve of gentle curvature . . . This is probably due to gradual changes of resistivity with depth." With this statement

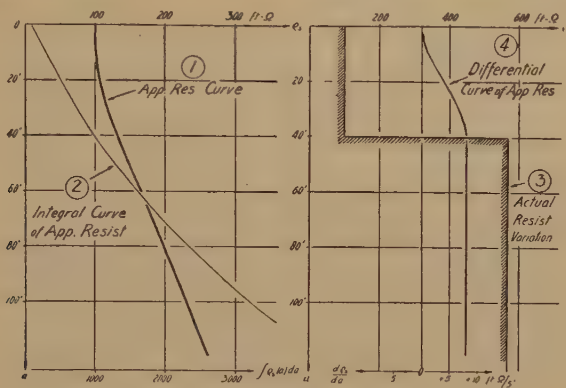

FIG. 19.

Mr. Moore repeats the error of the earlier interpreters of resistivity curves who thought that a gradual change in the resistivity curve itself was due to gradual changes in subsurface resistivities. That the curvatures in the integral curves are *not geological* in nature is readily proved by an analysis of *theoretical* curves for homogeneous media, and such an analysis will also show that the integrated curve does not consist of straight-line portions.

To illustrate this point I have calculated the apparent resistivity depth curves for a poor conductor overlain by a good conductor (Fig. 19) and for a good conductor covered by a poor conductor (Fig. 20). For the three-layer case, I have used two of Hummel's curves; one in which a good conductor is interbedded between an intermediate conductor above and a poor conductor below (Fig. 21), and one in which a poor conductor is interbedded between an intermediate conductor above and a good conductor below (Fig. 22). The last two figures correspond to Mr. Moore's Figs. 4 and 5, but our conclusions relative to curve interpretation are quite at variance with Mr. Moore's.

In Fig. 19, curve No. 1, which is the apparent resistivity curve for a poor conductor covered by a good conductor, shows the familiar asymtotic approach to the true underlayer resistivity for very large electrode separations. For the region shown in the figure, the last

part of the curve is practically straight. The integral curve, No. 2, obtained by graphical integration, does not show a straight line anywhere. It is true that the first part may appear to be a straight line and might be approximated by a straight line for a portion of its trend, but it would be difficult to place a straight line on the last part of the curve because it has a uniform curvature for the region indicated. In other words, unless it were known beforehand that the depth of the interface is 40 ft., it would be difficult to determine that depth by a straight line; particularly if not the portion of the curve immediately below 40 ft. but a deeper portion of the curve were used.

The reason why the first part of the curve seems to be a straight line is that the first part of curve No. 1 stays approximately at a constant value. It is readily proved that the integrated curve cannot consist of straight-line portions. If that were true, the apparent resistivity curve, which represents the derived curve of the integral curve and therefore indicates the slope of the integral curve, would have to show constant values for electrode intervals for which a straight-line slope is claimed in the integral curve. Incidentally, the electrode separations have in all diagrams been assumed to be equivalent to depths of penetration. In the second part of Fig. 19 the actual variation of subsurface resistivities with depth is indicated by curve No. 3, as is the differential curve of apparent resistivity (curve No. 4), which was derived from curve No. 1 by graphical differentiation. These differential curves have been plotted for all cases discussed herein and will be treated together at the end of this discussion.

In Fig. 20 the apparent-resistivity depth curve has been calculated for the actual resistivity depth variation shown in curve 7. The relations indicated for the preceding case are here even more apparent than they were before. The integral curve shows a fairly uniform curvature, particularly in its lower portions. Again the reason why the first part may appear to be a straight line is that there the curve No. 5 shows only a small variation of apparent resistivity with electrode separation. Because of the curvature of curve No. 6 for the larger separations, it would be very difficult to find a straight line tangent to it that would give the correct intersection with the straight-line approximation for the overburden at 40 ft. As a matter of fact, if the depths were not known beforehand it would be very doubtful whether the correct depths could be obtained by straight-line approximation.

In Fig. 21, No. 9 is the apparent resistivity curve calculated by Hummel for the actual resistivity variation indicated by No. 11. The integral curve is No. 10. The latter may be approximated satisfactorily by a straight line for its immediate near-surface portion, but it would be doubtful whether the correct depth of 40 ft. could be obtained by a straight-line approximation of the last part of the curve. Comparison of curve 10 with Mr. Moore's Fig. 4 shows that he did not go out far enough with his straight-line approximation, else the difficulty would have been noticed immediately.

The same is true for Mr. Moore's Fig. 5, which treats the same case shown by curves

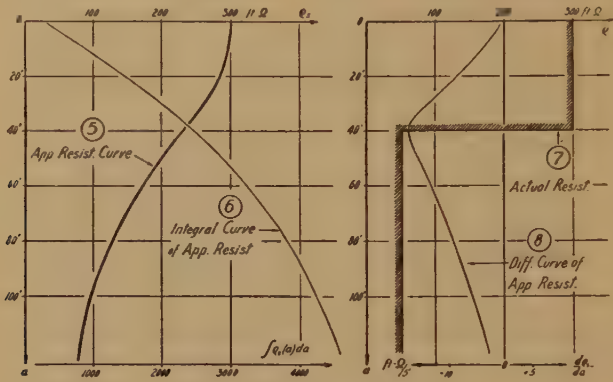

FIG. 20.

13 and 14 of Fig. 22. The lower part of the integral curve No. 14 is curved to such an extent that in practice it would not be possible to find the correct depth of 40 ft. by any straight-line approximation; one would not know beforehand which one of the many possible tangents to use.

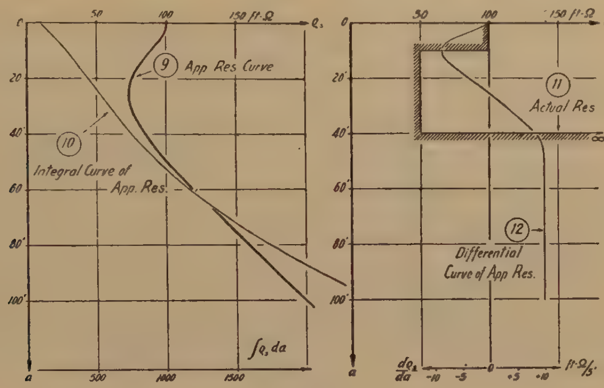

FIG. 21.

The obvious difficulty in trying to approximate a smooth curve by straight lines lies in the fact that the correct tangent cannot be determined accurately. If immediately adjacent portions are used the slope of these straight lines differs so little as to limit the usefulness of the depth determination. The straight-line approximation has the disadvantage that if more than the correct number of tangents are placed on the curve, *interfaces are simulated which actually do not exist.* For instance, the last part of the integral curve No. 14 could be approximated by at least three straight lines; by Mr. Moore's method there would be no way of knowing that there are no more interfaces below 40 feet.

The situation may be further clarified by referring to a statement previously made; namely, that the integral curve can be a straight line only in the interval in which the derived curve, which is the apparent resistivity curve, does not change in value. That, however, happens only if the apparent resistivity becomes equal to the actual resistivity. This is illustrated by curves 17 and 18 in Fig. 22. Curve 17 shows the straight-line approximation of curve 14 by Mr. Moore (which is incomplete since it omits the lower portion of the curve). If now the apparent resistivity curve No. 13 did have the trend of the actual resistivity variation shown in curve 15, then and only then would the integral curve consist of straight-line portions and it would, furthermore, deviate considerably from the straight-line approximation of the integral curve of the apparent resistivity (curve No. 18).

There may possibly be some usefulness in the integrated curve if the geologic situation is known sufficiently beforehand so that the interpretation on the basis of the integral curve may be limited to one and possibly two interfaces. In that case any interpretation based on the integral curve would have to exclude the deeper portions of the apparent resistivity curve.

It seems to me that there are too many unknown factors and too many temptations of arbitrariness in this method to make it of great practical value as a unique method of depth interpretation. I am inclined to believe that the *opposite* procedure—that is, the differentiation of the apparent resistivity curve—might give more reliable results, since it involves no guesswork.

In Fig. 19, curve No. 4 (obtained by graphical differentiation from curve No. 1) indicates the interface at 40 ft. probably more uniquely than a straight-line approximation of curve No. 2 would do. In Fig. 20 curve No. 8 gives a much better and more unique indication of the interface than a straight-line approximation of curve No. 6. In Fig. 21 the differential curve No. 12 gives a good indication of the first interface and a fair approximation of the

second interface, and in Fig. 22 the differential curve No. 16 gives a good indication of both the upper and lower interface. It is well known, of course, that from the practical point of view in an area where the near-surface beds changed very rapidly from place to place owing to terrestrial sedimentation conditions. In no case was a curve found with any abrupt

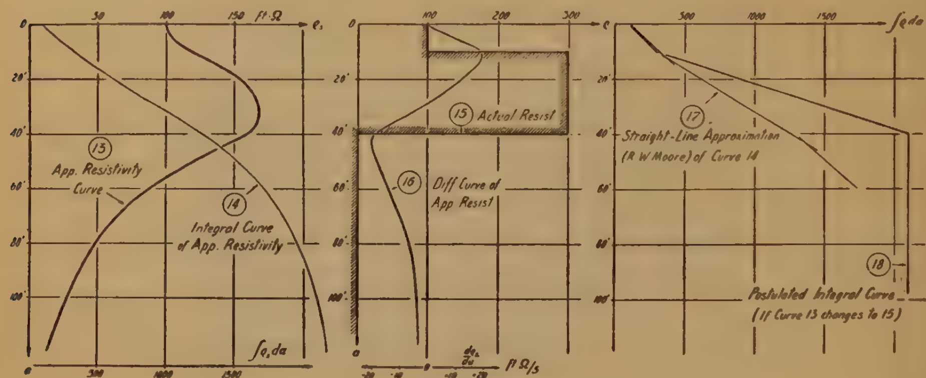

FIG. 22.

the differential curve would have a tendency to emphasize small and accidental resistivity variations. It would be necessary to smooth these out in the apparent resistivity curve before graphical differentiation is attempted. In spite of this difficulty I believe that the chances of error in smoothing out the apparent resistivity curve are not as great as those involved in trying to fit one or more straight-line tangents to a uniformly curved line.

This brings up a point that has been discussed frequently before the Institute; namely, whether the apparent resistivity curve is smooth or has breaks corresponding to the interfaces. I do not concur with Mr. Moore when he says that "in many instances in connection with shallow work abrupt breaks in the apparent-resistivity electrode-spacing curves have been found which when interpreted in this manner, give a reasonable indication of the position of the interface." In my own experience, this view is not supported by the theory nor by tank experiments, nor by acurately made field measurements. Certainly any inhomogeneities in the electrical characteristics of layers would show up more in tanks filled with sand or clay than in the field, owing to the difference in relative dimensions. Two years ago we had an opportunity to make many hundreds of shallow resistivity measurements (in which the maximum depth of penetration was 25 ft.) breaks, and depth interpretations were made by the conventional methods of analysis with accuracy and speed. Abrupt changes in the resistivity curve are generally due to variations in contact resistance and may be discovered and eliminated by modifying the technique so that the potential electrodes remain at a given location while the current electrodes are moved.

Frankly, I do not see much reason for extensive objections against analytical methods of depth determinations. It is admitted that the Tagg method may be slow. On previous occasions I have called attention to another interpretation method, which is both analytically correct and, for extensive projects, even faster than Mr. Moore's integration method. This method is based on a calculation of a family of curves for a given project where the surface resistivity and the underlayer resistivity are known and remain sufficiently constant. Fig. 23 show such a family of curves calculated for a bedrock exploration project, together with the superposed field curves. In cases of this nature depths to bedrock may be determined speedily and accurately by interpolation.

R. W. MOORE (author's reply).—Mr. Wilcox mentions the application of the cumulative curve method of analysis to old field data in his files. It would seem that a rather definite check

upon the proposed method of analysis could be had if a sufficient number of practicing geophysicists would do likewise, thus proving to their own satisfaction its possible usefulness or lack of utility in their own exploration work. Such information would have its greatest value if given adequate publicity.

Dr. Roman raises the question of the "personal equation." Many curves were plotted and replotted to satisfy, to some extent at least, the uncertainty in the writer's mind regarding this ever present factor. This influence may be a factor in other methods of analysis, however, and the need for caution is constantly with us.

Lieutenant Holser suggests that the proposed method of analysis is quite similar to the old "potential bowl" theory. In this he is correct, since the assumptions inherent in the original Gish-Rooney attack on the problem still prevail.

Regarding his criticism of the published curves, many instances occur where intersecting tangents (or straight lines approximating tangents) may be drawn with one or more individual points in the cumulative curve falling off the straight lines in the region of curvature involved. In the writer's experience the maximum rate of change in resistivity and the resultant change of curvature of the cumulative curve appear to occur at a depth that approximates that of the interface involved

In simple two-layer problems the initial tangent is usually rather definitely controlled by its beginning at the origin and/or by the first few points on the cumulative curve. In Fig. 3 the initial tangent was so controlled.

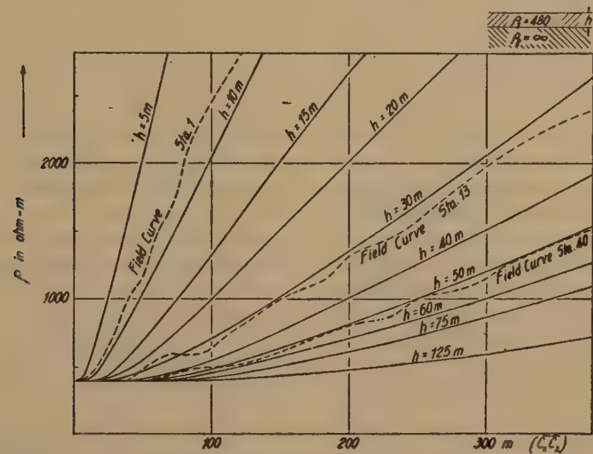

FIG. 23.—SUPERPOSITION DIAGRAM FOR INTERPRETATION OF RESISTIVITY-DEPTH CURVES. (*From Geophysical Exploration*, 733.)

The second line, in this instance, was drawn to include as many points as possible beyond the region of increasing curvature. Experience will dictate the propriety of giving less weight to the individual points falling off the lines in the region of curvature.

With regard to Fig. 6, the writer has frequently obtained straight-line curves such as that shown for station 1. The cumulative curve method has proved rather successful in the analysis of such curves. Direct control data are required, however, in an intelligent use of any empirical method. The curve for station 2 was recognized as being somewhat questionable with regard to the straight lines drawn. In the absence of control data, or any knowledge of existing conditions, this curve would be hard to interpret. In a given area, however, the analysis of a considerable number of such curves, when correlated with a drill record, may result in satisfactory interpretation if studied as a group. Both lines in the graph for station 2 could have been drawn on slightly different slopes, their intersection, however, would be at a depth of 90 to 100 feet.

The data for the two-layer model of Fig. 7 were not extensive enough to adequately control the second straight line shown. Two

or more additional points on the cumulative curve, in this instance, would have been of value. The same criticism is applicable to the curves mentioned in connection with Fig. 8.

Referring to Fig. 12, it should be stated that the origin as an initial point is not always proper. There are times when the initial resistivity value obtained for the first electrode setting is considerably out of line with subsequent resistivity values obtained involving similar but more moist materials at some depth. Where such conditions exist no attempt is made to include the origin in the initial straight line. In the curve for hole 14 of Fig. 8 the data for the first 50 ft. were lacking, hence the origin could not be given any significance. No doubt a curve such as that for hole No. 13 would have been obtained if the resistivity values for the first 50 ft. had been available.

The data for Fig. 15*D* seemed to be significant in the light of direct check data for the general area being investigated. Curves *A*, *B*, and *C* of Fig. 16 are in rather complete accord with the suggested method of analysis outlined in the original paper

Referring to Fig. 18, the field data were obtained in 1935 and were incomplete in the depth ranges of 24 to 36 in. Considerable weight was given the points at 24 and 36 in., which might or might not have proved to be a valid procedure had data for the intermediate points been available.

With reference to statements made by Dr. Heiland regarding "a generally smooth curve of gentle curvature," it is felt that the contention must be upheld that there is a change more or less gradual that sometimes occurs in a soil that is reflected by a corresponding change in resistivity Owing to atmospheric conditions, root structure, and the natural process of growing plants, a soil often may be somewhat dry and of high resistance in regions at or near its surface but with more favorable conditions of moisture it may possess an appreciably lower resistivity at greater depths. Thus for an over-all depth to solid rock of about 15 ft., using a 3-ft. electrode interval, data may be obtained for which the cumulative curve may show a slight curvature downward for the first two or three settings of the electrodes, and a much more pronounced curvature upward as the depth of the rock is approached. Because of these shallow surface conditions, it is necessary to ignore the effect of the first point on many curves and draw the initial straight line without regard to its passing through the origin.

The only sure way to determine the value of a particular method of analysis is to apply it to numerous field data obtained for a variety of field conditions for which there are ample direct check data available. The writer was somewhat disappointed that no attempt was made by Dr. Heiland to obtain intersections on each of his cumulative curves in the manner outlined in the original paper. A very close check was obtained for curve 2 of his Fig. 19, the straight lines drawn on an enlarged reproduction of his figure intersecting at about 40 ft. A somewhat less satisfactory result was obtained for his curve 6 of Fig. 20, a depth of 37 ft. being indicated. No attempt was made to interpret his curves 10 and 14 of Figs. 21 and 22, respectively, since these data had already been presented in the original paper.

In discussing his Fig. 19, Dr. Heiland says that "unless it were known beforehand that the depth of the interface is 40 ft., it would be difficult to determine that depth by a straight line; particularly if not the portion of the curve immediately below 40 ft. but a deeper portion of the curve were used." As stated in the original paper, the first portion of any cumulative curve must be used; that is, the portion in the vicinity of the change in resistivity as exhibited by the Gish-Rooney curve. Proper use of much deeper portions of the curve can only be established by actual correlations in a study of a given terrain. In shallow explorations, up to 50 ft. but for the most part bordering on 10 to 20 ft., direct correlations have always been used by the writer as control in analyzing the curves obtained, and the approximate depth, or probable depth, is, therefore, a known factor in any given area under investigation.

Although admitting the possibility of difficulty in establishing straight lines in some instances, it has been the writer's experience that the initial straight line is usually rather easily determined and the second straight line (in a two-layer case) generally can be located with some degree of integrity, particularly when proper control has been established. Some difficulty may be expected in attempting

to apply a particular method of analysis to problems involving three or more layers, whether using empirical methods or theoretical curves. The problem of adequate control data naturally becomes more troublesome as the deeper structures are involved.

Dr. Heiland states that "there may possibly be some usefulness in the integral curve if the geologic structure is known sufficiently beforehand so that the interpretation on the basis of the integral curve may be limited to one and possibly two interfaces." In making this statement he appears to concur with the general statements made by the writer in the body of the paper under discussion and emphasized in the summary.

Referring to the question of the significance of abrupt breaks in earth-resistivity curves, the writer has obtained one or two thousand curves in shallow explorations since 1933 and, as stated previously, many of the data were interpreted using the Gish-Rooney curve and rather abrupt breaks appearing therein. In the writer's experience the curves having abrupt breaks were obtained in shallow explorations.

* See *Public Roads* [(July-Aug.-Sept., 1944) **24**, 29, Fig. 4, for examples of curves obtained over a gravel deposit.]

In 1942 the Public Roads Administration completed an exploration project for the Bureau of Ships, Navy Department, covering some 150 acres. From the resistivity data, rock-elevation contours at 2-ft. intervals over the entire area were predicted. The cumulative method of analysis was used in interpreting the curves obtained by resistivity tests, examples of which were shown in Fig. 16. Excavations begun in August 1944 in connection with an extensive building program at the Taylor Model Basin in the area involved have made available a large amount of correlating data in recent months. Based upon rock-surface cross sections as revealed by excavation, the overburden as computed from the rock contour and surface maps prepared from resistivity data in 1942 checked within less than one per cent the actual excavation quantities for an area 150 by 1600 ft. About 90,000 cu. yd. was involved. A detailed subsurface survey of an adjoining tract of about 50 acres has recently been completed.

The writer wishes to express his appreciation of all criticism, favorable or otherwise. Perhaps a wider publicity of other simple and more practical methods of analyzing resistivity data will result and both the writer and others will be benefited thereby.

The Interpretation of Earth-resistivity Measurements

BY MORRIS MUSKAT,* MEMBER A.I.M.E.

(New York Meeting, February 1945)

ABSTRACT

THE method of R. W. Moore[1] for determining subsurface interfacial depths by means of integrated curves of apparent resistivity has been analyzed theoretically. It is found that the only unique tangents that can be drawn to such curves are the asymptotes at infinite electrode spacing and the tangents through the origin at vanishing electrode spacing. Explicit expressions have been derived for the relationship between the electrode spacing at the points of intersection of these tangents and the thickness of the surface strata as a function of the conductivity parameters for the two-layer and three-layer earths. It is found that in all cases the electrode spacing at the points of intersection will exceed 3/2 of the thickness of the surface layer, and may even become indefinitely large as the resistivity of the deepest layers increases as compared with that of the surface layer. These results do not agree with the empirical findings of Moore that the intersection of the tangent lines fall at an electrode spacing very approximately equal to the thickness of the surface layer.

INTRODUCTION

In a recent paper, R. W. Moore[1] proposed a new method for the analysis and interpretation of earth-resistivity measurements. This consists essentially in plotting against the electrode separation of a Gish-Rooney system the integral of the apparent resistivity with respect to the electrode spacing, and observing the breaks in the integral curves. Specifically, tangents are drawn to the various segments of the integral curves, which show appreciably different slopes, and the intersections of these tangents are used as indications of the depths of the various underlying strata. By numerous examples Moore has shown that the electrode separation at the first intersection so found agrees very closely with the depth of the bottom of the surface layer. Moreover, in a number of instances the intersections for greater electrode spacings seemed to correspond to the depths of deeper beds.

From a strictly empirical point of view, the procedure proposed and demonstrated by Moore appears to be particularly interesting because of its simplicity as well as its apparent accuracy. Moreover, such a simple method would be especially valuable in view of the well-known difficulties heretofore encountered in the quantitative interpretation of resistivity data. It therefore seems appropriate to attempt a mathematical analysis of the problem to see whether the integral method of Moore has a sound basis. Such an analysis is presented here.

Even on cursory consideration, it is clear that the remarkable successes observed by Moore in the application of his method are indeed surprising. For it depends upon the determination and choice of the slopes of smooth and continuous curves, which by their nature must show even more gradual variations than the original apparent-resistivity plots that are already so difficult to interpret quantitatively. It is well established, of course,

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Manuscript received at the office of the Institute May 8, 1944. Issued as T.P. 1761 in November 1944.

* Gulf Research and Development Co., Pittsburgh, Pennsylvania.

[1] References are at the end of the paper.

that even for strictly discontinuous vertical resistivity variations of the subsurface strata the apparent resistivity, measured by Gish-Rooney or equivalent methods, will show continuous variations as the electrode spacings are increased to give greater and greater depth penetrations. This is a result of the inherent averaging effect of the diffused current distributions in the subsurface strata.

Examples of theoretically computed resistivity curves for two-layer systems are shown in Figs. 1 and 2 for several resistivity ratios. The data used in these plots up to values of $\frac{a}{h} = 5$ were taken from the tables of Roman,[2] while those for greater values were computed directly by the author. The ordinates are the ratios of the apparent resistivity to that of the surface, and the abcissas $\frac{a}{h}$ are the ratios of the inner electrode spacing of the Gish-Rooney system to the thickness of the surface layer. It will be seen from these that whereas the apparent resistivity does asymptotically approach the true resistivity of the bottom layer as the electrode spacing is increased, the transition range may be quite extended, especially when the resistivity of the second layer is large as compared with that of the surface stratum. In particular, when the ratio of these two is 9, the apparent resistivity is only 93 per cent of that of the bottom layer, even though the electrode spacing is 40 times as great as the thickness of the surface stratum. It is clear that the integrals of such curves will be even more slowly varying functions of the electrode spacing, and hence subject to still greater uncertainty with respect to the finding of the breaks in the curves either visually or by drawing tangents to the curves.

In principle, the apparent-resistivity integral curve should asymptotically approach a linear behavior, with a slope equal to the resistivity of the deepest layer. Moreover, for small electrode spacings the integral curves should also be approximately linear, with slopes corresponding to the resistivity of the surface layer. There will thus arise a well-defined

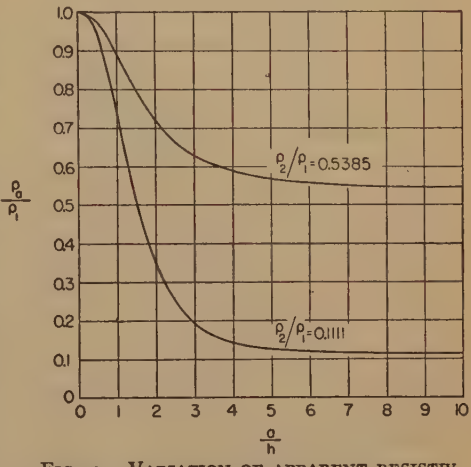

FIG. 1.—VARIATION OF APPARENT RESISTIVITY WITH ELECTRODE SPACING IN TWO-LAYER SYSTEMS.

ρ_a/ρ_1 = (apparent resistivity)/(resistivity of surface layer).
ρ_2/ρ_1 = (resistivity of bottom layer)/(resistivity of surface layer).
a/h = (electrode spacing)/(surface-layer thickness).

point of intersection between the straight line through the origin and tangent at the origin to the integral curve, and the linear asymptote of the integral curve for large electrode spacings. Theoretically, it would appear that it is only this intersection that can be unambiguously fixed and well defined in any reasonable way in both two-layer and multilayer systems. If there is any theoretical significance to the location of the intersection points by the method of Moore, it is this point that should lie at an electrode spacing equal to the thickness of the surface layer. Unfortunately, however, as will be seen presently, the theory shows that no such identity exists. In the first place, as also may be expected from general considerations, it turns out that the point of intersection depends upon the resistivity contrast of the subsurface strata.

Indeed, in the two-layer systems, it increases linearly with the ratio of the resistivity of the bottom layer to that of the surface layer. Moreover, the very minimum value of the electrode spacing for the point of intersection turns out to be three halves of the thickness of the surface layer, and becomes as great as 15 times that thickness when the resistivity of the bottom stratum is nine times that of the surface layer.

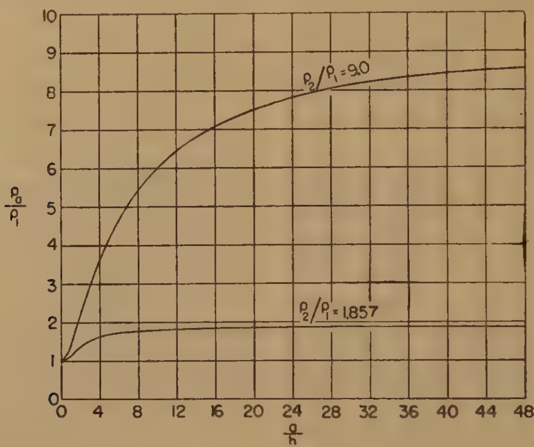

FIG. 2.—VARIATION OF APPARENT RESISTIVITY WITH ELECTRODE SPACING IN TWO-LAYER SYSTEMS.
ρ_a/ρ_1 = (apparent resistivity)/(resistivity of surface layer).
ρ_2/ρ_1 = (resistivity of bottom layer)/(resistivity of surface layer).
a/h = (electrode spacing)/(surface-layer thickness).

ANALYTICAL THEORY

Denoting the internal electrode spacing in the Gish-Rooney system by a, the conventional definition of the apparent resistivity is given by:

$$\rho_a = \frac{2\pi a \Delta V}{I} \qquad [1]$$

where I is the current passing through the ground and ΔV is the voltage drop between the two potential electrodes. This may also be expressed as:

$$\Delta V = 2\{V(s) - V(2s)\} \qquad [2]$$

where $V(s)$ is the potential at s, due to a current source of strength I. To evaluate these potentials and the corresponding resistivity, it will be convenient to use the analytical representations developed by the author[3] in a general analysis of the resistivity problem. In the latter work, integral expressions were derived for the potential fields due to current electrodes, and expressed as functions $\Phi(a)$. For small values of the latter these can be approximated by:

$$\Phi(a) \sim 2h/a \qquad [3]$$

which corresponds to a current

$$I = 4\pi h/\rho_1$$

where h is the thickness of the surface layer, and ρ_1 is its resistivity. Accordingly, Eq. 1 in this notation becomes:

$$\rho_a = \frac{\rho_1 a}{h}[\Phi(a) - \Phi(2a)] \qquad [4]$$

Now if $\frac{\rho_2}{\rho_1} \equiv \tanh\gamma < 1$, it was shown that the function $\Phi(a)$ could be expressed

as:

$$\Phi(a) = 2\int_0^\infty \tanh(\alpha+\gamma) J_0\left(\frac{a\alpha}{h}\right) d\alpha$$
$$= 2\frac{\rho_2}{\rho_1}\frac{h}{a} + 2\int_0^\infty \{\tanh(\alpha+\gamma) - \tanh\gamma\} J_0\left(\frac{a\alpha}{h}\right) d\alpha \quad [5]$$

where J_0 is the zero order Bessel function. It readily follows that the apparent resistivity will be given by:

$$\rho_a = \rho_2 + \frac{2a\rho_1}{h}\int_0^\infty \{\tanh(\alpha+\gamma) - \tanh\gamma\} \left\{J_0\left(\frac{a\alpha}{h}\right) - J_0\left(\frac{2a\alpha}{h}\right)\right\} d\alpha \quad [6]$$

To follow the empirical procedure of Moore, one must now integrate the apparent resistivity with respect to a. This may be done in a formal analytical manner, with the result:

$$R_a = \int_0^a \rho_a\, da = \rho_2 a + 2\rho_1 a \int_0^\infty f(\alpha) \left\{J_1\left(\frac{a\alpha}{h}\right) - \frac{1}{2}J_1\left(\frac{2a\alpha}{h}\right)\right\} d\alpha$$

where:

$$f(\alpha) = \frac{\tanh(\alpha+\gamma) - \tanh\gamma}{\alpha} \quad [7]$$

In principle, this equation will give the complete behavior of the integral curve as a function of a throughout the range of the latter. Of particular interest here, however, is the asymptotic behavior of R_a, which is necessary to fix the tangent line. For this purpose we note first that Eq. 7 can be transformed into:

$$R_a = \rho_2 a + \frac{3}{2}\rho_1 h f(0) + 2\rho_1 h \int_0^\infty f'(\alpha) \left\{J_0\left(\frac{a\alpha}{h}\right) - \frac{1}{4}J_0\frac{(2a\alpha)}{h}\right\} d\alpha \quad [8]$$

Now it may be readily shown that the integral remaining in Eq. 8 will be of the order of $\frac{1}{a}$ for large values of a. Hence, asymptotically, we obtain:

$$R_a = \rho_2 a + \tfrac{3}{2}\rho_1 h f(0) = \rho_2 a + \tfrac{3}{2}\rho_1 h(1 - \rho_2^2/\rho_1^2) \quad [9]$$

This is obviously also the equation for the asymptotic tangent to the integral apparent-resistivity curve.

For small values of a, it is clear that the integral curve will be tangent to the line $R_a = \rho_1 a$. Hence the point of intersection will be given by

$$a_i = \tfrac{3}{2} h(1 + \rho_2/\rho_1) \quad [10]$$

from which the depth h may be calculated as:

$$h = \frac{2a_i}{3(1 + \rho_2/\rho_1)} \quad [11]$$

Thus the electrode spacing at the point of intersection will always be greater than $\tfrac{3}{2}$ times the thickness of the surface layer, and the latter will always be less than $\tfrac{2}{3}$ the spacing at the point of intersection.

By very similar procedures it may be shown that Eqs. 10 and 11 also apply for two-layer earths in which $\frac{\rho_2}{\rho_1} > 1$. It thus appears that the only point of intersection of tangent lines to the integral apparent-resistivity curves which are well defined analytically will always give an electrode spacing greater than the top-layer thickness by an amount that may vary from 50 per cent to infinity.

To verify that the purely analytical derivation given above of the asymptotic behavior of the integral-resistivity curve and the resultant intersection points are correct, the four theoretically calculated resistivity curves of Figs. 1 and 2 were graphically integrated for direct application of the method of Moore. The results are shown in Figs. 3 and 4. The ordinates in these figures are the integrated values of apparent resistivity divided by the product of the resistivity of the surface layer and the thickness of the latter. The abscissas

are the ratios of the electrode spacing to the thickness of the surface layer. In Fig. 3, the solid straight line through the origin, of slope unity, represents the

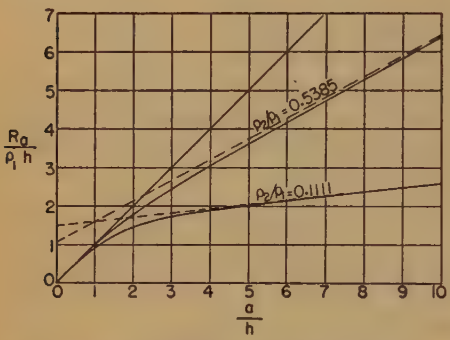

FIG. 3.—VARIATION OF INTEGRATED APPARENT RESISTIVITY WITH ELECTRODE SPACING.

$R_a = \int_0^a \rho_a \, da$; ρ_a = apparent resistivity; a = electrode spacing; h = thickness of surface layer; ρ_1 = resistivity of surface layer; ρ_2 = resistivity of bottom layer.

Straight solid lines are tangents through origin. Straight dashed lines are asymptotic tangents.

ratios of the bottom to surface resistivity equal to 0.5385 and 0.1111. The dashed straight lines are the asymptotic tangents drawn according to Eq. 9. It will be readily seen that these dashed lines actually approach tangency to the integrated curves for large electrode spacings and hence give intersections with the straight line through the origin according to Eq. 10. For the two curves shown in Fig. 3, these are at values of $\frac{a}{h} = 2.31$ and 1.67.

In Fig. 4 are shown similar verifications of the analytical derivations in cases where the ratios of bottom to surface resistivity are 1.857 and 9. Because of the change in ordinate scales, two individual straight lines have been drawn through the origin. Here the intersections of the straight-line tangents are at values of the abscissa equal to 4.28 and 15, according to Eq. 10. It will be noted, however, that whereas the asymptotic behavior is developed almost completely in the case of the resistivity ratio 1.857 for an electrode spacing equal

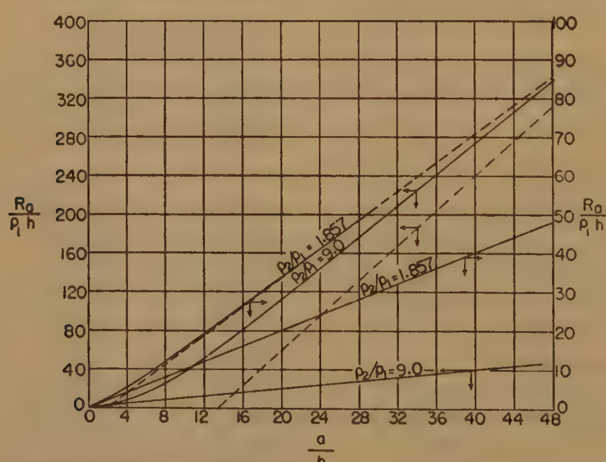

FIG. 4.—VARIATION OF INTEGRATED APPARENT RESISTIVITY WITH ELECTRODE SPACING.

$R_a = \int_0^a \rho_a \, da$; ρ_a = apparent resistivity; a = electrode spacing; h = thickness of surface layer; ρ_1 = resistivity of surface layer; ρ_2 = resistivity of bottom layer.

Straight solid lines are tangents through origin. Straight dashed lines are asymptotic tangents.

tangent at the origin to the integral curves. The latter are given by the solid curves for to 20 times the thickness of the surface layer, there is still a great divergence

between the theoretical asymptote and the actual integral curve for a resistivity ratio of 9 even up to an electrode spacing 50 times as great as the thickness of the upper layer. A similar—though smaller—variation in rate of approach to the asymptotic behavior may be observed in Fig. 3. It is clear, therefore, that while the theoretical relations of Eqs. 9 and 10 give perfectly definite values for the asymptotic behavior and the resultant intersections, the approach to such asymptotic behavior of the actual integral curves may be so slow that the drawing of the tangents may be quite uncertain without using electrode spacings that are much larger than those normally used for shallow resistivity studies. However, unless the asymptotic behavior is actually developed, local tangents may be drawn anywhere along the integral curve with resultant wide variation of values found for the points of intersection. Theoretically, therefore, the latter should have such a lack of uniqueness that it is, indeed, remarkable that Moore was able to choose in so many cases the points of tangency as to give electrode spacing intersections equal to the thickness of the surface layer.

The analytical method for deriving the asymptotic behavior of the integral apparent-resistivity curve can also be applied to multilayer systems. A brief outline of the analysis for three-layer earths will demonstrate this. Thus, in the paper previously referred to, it is shown that in a three-layer earth the individual potential functions corresponding to Eq. 5 may be expressed as:

$$\Phi(a) = \frac{2h_1}{a} + 2\int_0^\infty f(\alpha) J_0\left(\frac{a\alpha}{h_1}\right) d\alpha \quad [12]$$

where here h_1 is the thickness of the surface stratum, and $f(\alpha)$ is a function defined by Eq. 25 of the previous paper. Forming the value of the apparent resistivity, as was done for the two-layer earth, then integrating and passing to the asymptotic limit, it is finally found that the asymptotic behavior for R_a is given by

$$R_a = \int_0^a \rho_a da = \rho_3 a - \frac{6\rho_1 h_1[(k_2 + k_3 h)(1 - k_2^2) + k_2(k_2 + k_3)^2]}{(1 - k_2)^2(1 - k_3)^2} + o\left(\frac{1}{a}\right) \quad [13]$$

where:

$$k_2 = \frac{\rho_2/\rho_1 - 1}{\rho_2/\rho_1 + 1}, \quad k_3 = \frac{\rho_3/\rho_2 - 1}{\rho_3/\rho_2 + 1}$$

ρ_1, ρ_2, and ρ_3 being the resistivities of the surface, middle, and bottom layers, respectively, and h the ratio of the depth to the bottom layer to the thickness of the surface stratum. On determining the point of intersection of the asymptotic tangent given by Eq. 13 with the tangent through the origin, it is readily found that the electrode spacing for the point of intersection will be:

$$a_i = \frac{3h_1[(k_2 + k_3 h)(1 - k_2^2) + k_2(k_2 + k_3)^2]}{(k_2 + k_3)(1 - k_2)(1 - k_3)} \quad [14]$$

It will be readily verified that Eq. 14 reduces to Eq. 10 for the two-layer earth, when in the former either k_2 or k_3 is set equal to 0.

It will be clear from Eq. 14 that Moore's empirical result that the electrode spacing at the first intersection is equal to the surface-layer thickness has no more theoretical validity for the three-layer than for the two-layer earth. In fact, in the case where the bottom zone resistivity is infinite, and $k_3 = 1$, a_i becomes infinitely large. For the other extreme case, where the resistivity of the bottom stratum is 0, and $k_3 = -1$, it may be easily shown that a_i increases with k_2 and is always greater than $\frac{3}{2}h_1$. Similar results evidently would be obtained for even more complex vertically stratified conducting systems.

On the other hand, it may be noted that when the resistivity of the bottom layer is the same as that of the surface zone ($k_3 = -k_2$), Eq. 14 breaks down, and

there is, in fact, no point of intersection of the asymptotic tangent and the tangent through the origin. This parallelism between the two tangents will, of course, arise in all multilayer systems in which the surface and deepest strata have the same resistivity.

With respect to the general question of the value of the method introduced by Moore, it is to be observed that, when applied correctly, it does provide a very convenient procedure for determining the interface depth in a two-layer system, as given by Eq. 11. For multilayer problems, however, it is doubtful whether it can be of value. Thus the determination of the resistivity of the surface and bottom layers by observation of the slopes of the tangents to the integral curves can of itself provide no advantage over the method of using the apparent-resistivity curves directly. And the procedure for the determination of depths by means of intersections of the tangent through the origin and the asymptotic tangent to the integral curve becomes virtually impossible for multilayer systems.

For example, Eq. 14 relates the electrode spacing at the point of intersection to the other physical constants of the system. But, as there are three of the latter, not determined by the tangent slopes—namely, the resistivity of the middle layer and the depths to the two interfaces—the single Eq. 14 will not determine any of them uniquely. Here it may be noted that no additional information is provided by the value of the ordinate intercept of the asymptotic tangent, for it may be readily shown that the latter is necessarily given by the product of the electrode spacing for the point of intersection into the difference between the interface and deepest layer resistivities.

In principle, one could study the deviation of the integral curve from its asymptotic curve given by Eq. 13. For example, in the three-layer system it may be shown that by including the next term in the asymptotic expansion, Eq. 13 becomes:

$$R_a = \rho_3 a + (\rho_1 - \rho_3)a_i + \frac{7\rho_3 h_1^2}{a(1 - k_2)^2(1 - k_3)^2} [k_3\{(1 - k_2)h + 2k_2\}^2 + k_2(1 - k_3)^2] \quad [15]$$

Hence, by plotting $a(R_a - R_b)$ vs. a^2, R_b being the second term in Eq. 15, the resultant ordinate intercept will give the value of the third term, and thus an additional equation between h_1, h, and ρ_2. Or, one could compute other integral functions of the apparent resistivity and obtain additional relationships between the unique features of such functions or curves and the physical constants of the system. It will be clear, however, that such procedures would involve considerable manipulation of the data and tedious algebraic processes for the determination of the physical data being sought. Moreover, in all such processes, to obtain unique asymptotic characteristics it would be necessary to determine apparent-resistivity data at very large electrode spacings, especially for high resistivities of the deepest layers. In general, it would be entirely impractical to attempt to reach the asymptotic behavior merely for the sake of obtaining information regarding the intermediate strata. It appears, therefore, that while the method of Moore does suggest an interesting approach to the problem of the interpretation of resistivity data, it is beset with such practical difficulties as would necessitate extreme caution and care when applying it as a geophysical method of prospecting.

Acknowledgments

The author is indebted to Dr. L. L. Nettleton for bringing to his attention the work of R. W. Moore, and for the opportunity of discussing with him a number of questions arising from that work.

References

1. R. W. Moore: An Empirical Method of Interpretation of Earth-resistivity Measurements. This volume, page 197.
2. I. Roman: Some Interpretations of Earth-resistivity Data. *Trans.* A.I.M.E. (1934) 110, 183–197.
3. M. Muskat: *Physics* (1933) 4, 129–147.

DISCUSSION

R. W. MOORE.*—The paper by Dr. Muskat is essentially a discussion of an empirical method of interpretation of earth-resistivity data recently proposed by the writer (this volume, p. 197). Dr. Muskat examines the proposed empirical method by applying it to theoretically computed resistivity curves and by means of analytical theory. Perhaps it should be emphasized that in the original presentation the method was described as empirical and without theoretical basis. Its use was illustrated by numerous examples. In these, data obtained by a number of diffierent investigators were analyzed by the method, including both two-layer and three-layer conditions. Although recommended primarily for two-layer formations it was indicated that the method of interpretation could be applied to a three-layer condition. In addition to the numerous examples given, it was stated that many other published data had been analyzed by the cumulative-curve method with about the same general degree of success. Since the examples given were typical, there seems to be no need for adding to them in this discussion.

In the method, as proposed, the point (or points) at which there are "breaks" in the cumulative curve is determined by the intersection of straight lines that are referred to as tangents. There is perhaps some reason for taking exception to the use of the term "tangent" when referring to these lines. This is emphasized by the discussion presented by Dr. Muskat.

Although Dr. Muskat suggests that, theoretically, the proposed method is without a sound basis, the fact remains that the value of any empirical method can best be determined by the success with which it can be applied to actual field data obtained under circumstances that permit a direct check against a known condition. This same criterion is equally applicable to theoretical methods. Thus it seems that Dr. Muskat's final word of caution on the application of the cumulative-curve method of analysis to data from geophysical prospecting is well taken. However, it should be expanded to include other methods of interpretation, since some direct correlation is necessary if any method is to be used with assurance.

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Flow of Heat from an Intrusive Body into Country Rock

By C. E. Van Orstrand,* Member A.I.M.E.

(New York Meeting, February 1944)

An intrusive body is a mass of igneous rock that has migrated upward, presumably from great depths. Great variations in form, composition and depth of burial occur. It is not proposed in this paper to go into all of the details of the problem. Instead, it will be assumed here that the intrusive has the form and characteristics represented in Fig. 1.

According to W. H. Emmons,[1] minerals are not deposited in appreciable quantities below the "dead line." Important amounts of ores of virtually all metals may be found around summit cupolas, but only gold, copper and zinc (in limited quantities) are usually associated with trough cupolas. Most students of ore deposits agree that temperature changes are largely instrumental in precipitating many ores in the "hood" and that the difference in temperature between the intrusive and that of the country rock may be the chief factor in determining the mineralogy of a deposit. A problem then of some interest is to correlate the principal physical features of the intrusive with the phenomena of heat conduction as evidenced by the cooling curves and the isothermal surfaces.

Mathematical Theory

In order to show the possible application of heat conduction to the interpretation of the processes of metalliferous deposition associated with intrusives, it will be assumed that the intrusive is a large parallelopiped of dimensions, $2l$, $2m$, $2n$. The equation that represents the flow of heat from the parallelopiped into country rock ($v = 0$, $t = 0$), which has the same thermal properties as the intrusive, is[2,3]

$$\frac{v}{v_0} = \frac{1}{8}\left[\left[\frac{2}{\sqrt{\pi}}\int_0^{\frac{l-x}{2\sqrt{\kappa t}}} e^{-\alpha^2}d\alpha + \frac{2}{\sqrt{\pi}}\int_0^{\frac{-l-x}{2\sqrt{\kappa t}}} e^{-\alpha^2}d\alpha\right]\left[\frac{2}{\sqrt{\pi}}\int_0^{\frac{m-y}{2\sqrt{\kappa t}}} e^{-\beta^2}d\beta + \frac{2}{\sqrt{\pi}}\int_0^{\frac{-m-y}{2\sqrt{\kappa t}}} e^{-\beta^2}d\beta\right]\left[\frac{2}{\sqrt{\pi}}\int_0^{\frac{n-z}{2\sqrt{\kappa t}}} e^{-\gamma^2}d\gamma + \frac{2}{\sqrt{\pi}}\int_0^{\frac{-n-z}{2\sqrt{\kappa t}}} e^{-\gamma^2}d\gamma\right]\right] \quad [1]$$

In this equation, the origin, $x = 0$, $y = 0$, $z = 0$, is at the center of the parallelopiped.

v = temperature at point x, y, z, time t.
v_0 = initial temperature throughout the intrusive, $t = 0$.
κ = coefficient of thermal diffusivity.

α, β, γ are variables of integration.

Put $n = \infty$ in Eq. 1, and we have

$$\frac{v}{v_0} = \frac{1}{4}\left[\left[\frac{2}{\sqrt{\pi}}\int_0^{\frac{l-x}{2\sqrt{\kappa t}}} e^{-\alpha^2}d\alpha + \frac{2}{\sqrt{\pi}}\int_0^{\frac{-l-x}{2\sqrt{\kappa t}}} e^{-\alpha^2}d\alpha\right]\left[\frac{2}{\sqrt{\pi}}\int_0^{\frac{m-y}{2\sqrt{\kappa t}}} e^{-\beta^2}d\beta + \frac{2}{\sqrt{\pi}}\int_0^{\frac{-m-y}{2\sqrt{\kappa t}}} e^{-\beta^2}d\beta\right]\right] \quad [2]$$

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[1] References are at the end of the paper.

which represents the flow of heat from a rectangular volcanic neck or core into country rock, and furthermore, put $m = \infty$ in Eq. 2 and we have

$$\frac{v}{v_0} = \frac{1}{2}\left[\left[\frac{2}{\sqrt{\pi}}\int_0^{\frac{l-x}{2\sqrt{\kappa t}}} e^{-\alpha^2}d\alpha + \frac{2}{\sqrt{\pi}}\cdot \int_0^{\frac{-l-x}{2\sqrt{\kappa t}}} e^{-\alpha^2}d\alpha\right]\right] \quad [3]$$

which represents the flow of heat from a dike of thickness $2l$.

From the symmetry of the mass, and the uniform conditions under which it cools, it is evident that the highest temperatures are to be found on the axes. This is also evident from Eq. 1, for if we put any two of the coordinates equal to 0, the maximum value of the sum of the two probability integrals in each bracket is 2 ($t = 0$), and as this value is divided by 2, the maximum value of the product of the two bracket factors is one. This condition exists also for $t > 0$ when the intrusive is very large. That it is true for all values of t is readily seen by plotting the limits of integration on the probability curve. The area between the limits of integration will be found to be a maximum when $x = y = z = 0$.

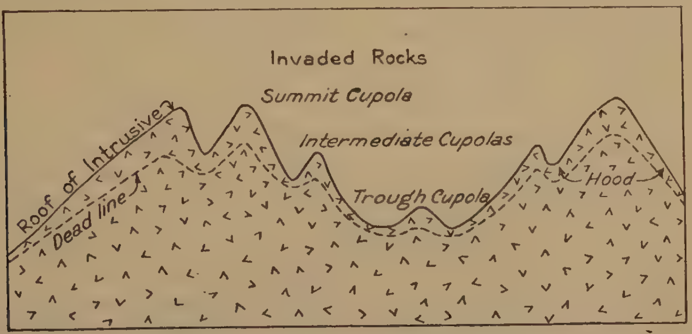
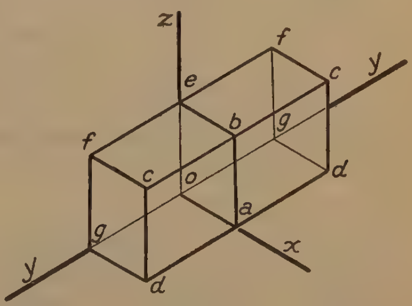


FIG. 1.—CROSS SECTION OF INTRUSIVE SHOWING SUMMIT, INTERMEDIATE AND TROUGH CUPOLAS. (*After W. H. Emmons.*[1])
Ore deposits may be concentrated near cupolas of each group.

NUMERICAL CALCULATIONS

Let it be assumed that the intrusive has the dimensions 20 by 200 by 2000 meters, and that the thermal constants for both the intrusive and the country rock are $k = 0.0042$, $\kappa = 0.0118$, values that represent the average silica igneous rock. The term v/v_0 gives percentages of the initial differences in temperature between the intrusive and the country rock. Some special values of v/v_0 computed from Eq. 1 are tabulated in Table 1. Referring to the accompanying sketch, which shows ¼ of an



intrusive in the form of a parallelopiped, the values in the columns *oa*, *og*, *oe* of the table are the values along the x, y, z axes for the time intervals, 1 yr., 9 yr. and 100 yr. The second column in the table contains the sum of the values of the two probability integrals in each bracket; that is, either $[P_x + P_x']$, $[P_y + P_y']$, or $[P_z + P_z']$, while the values in the other columns exclusive of *oa*, *og*, *oe*, are the values of v/v_0 along lines parallel to the axes at the distances given in column 1 for

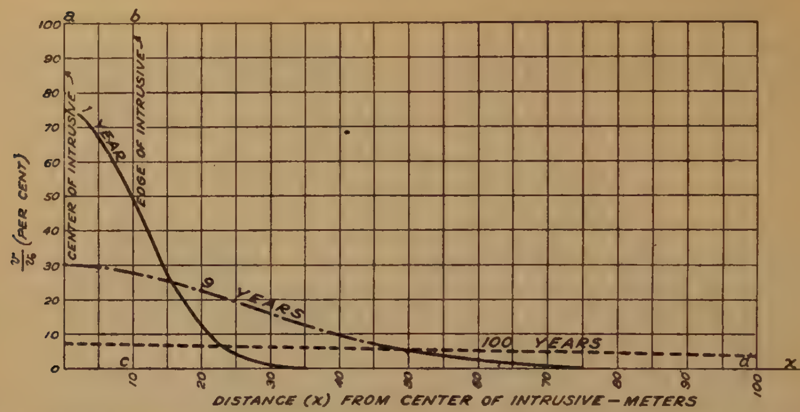


FIG. 2.—FLOW OF HEAT FROM AN INTRUSIVE (20 BY 200 BY 2000 METERS) IN THE x DIRECTION.

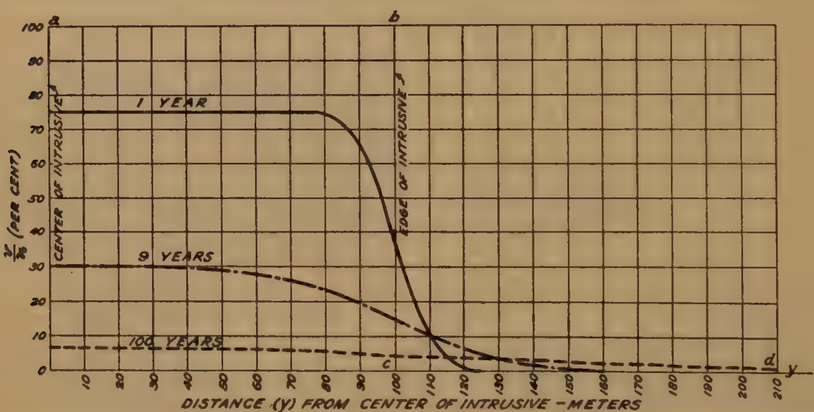


FIG. 3.—FLOW OF HEAT FROM AN INTRUSIVE (20 BY 200 BY 2000 METERS) IN THE y DIRECTION.

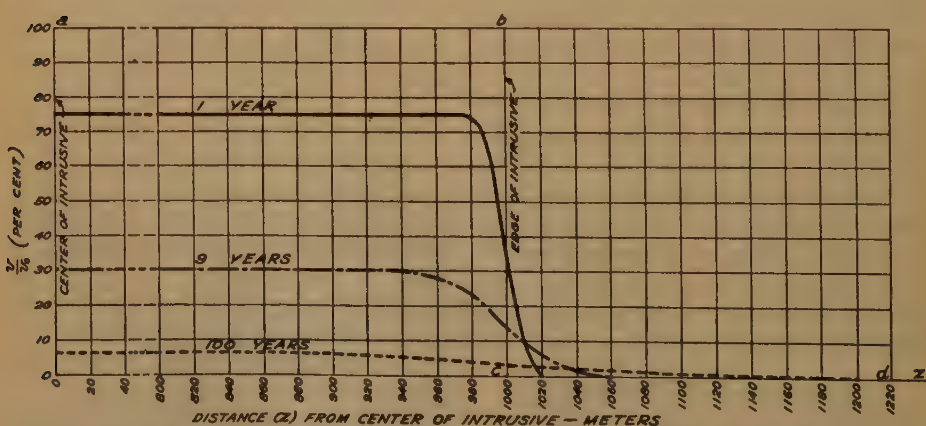


FIG. 4. FLOW OF HEAT FROM AN INTRUSIVE (20 BY 200 BY 2000 METERS) IN THE z DIRECTION.

the x, y, z coordinates, as the case may be, and are obtained by multiplying one of the values, $[P_x + P_x']$, $[P_y + P_y']$ or $[P_z + P_z']$ by the corresponding factor at the top of each column. This factor is the value of the product of the two remaining bracket expressions in Eq. 1, computed either for boundary lines of the parallelopiped or for traces of the coordinate planes on the boundary planes of the parallelopiped; that

TABLE 1.—*Values of v/v_0 along Certain Lines*

x Meters	t = 1 Year					x Meters	t = 9 Years				
	$P_x + P_x'$	*oa* 0.5	*eb* 0.25	*fc* 0.125	*gd* 0.25		$P_x + P_x'$	*oa* 0.49994	*eb* 0.24997	*fc* 0.125	*gd* 0.25
		$y = 0$, $z = 0$	$y = 0$, $z = n$	$y = m$, $z = n$	$y = m$, $z = 0$			$y = 0$, $z = 0$	$y = 0$, $z = n$	$y = m$, $z = n$	$y = m$, $z = 0$
0.0	1.50690	0.7534	0.3767	0.1884	0.3767	0	0.60138	0.3007	0.1503	0.0752	0.1503
2.5	1.46770	0.7338	0.3669	0.1835	0.3669	5	0.59081	0.2954	0.1477	0.0738	0.1477
5.0	1.35549	0.6777	0.3389	0.1694	0.3389	10	0.56019	0.2801	0.1400	0.0700	0.1400
7.5	1.18536	0.5927	0.2963	0.1482	0.2963	15	0.51264	0.2563	0.1282	0.0641	0.1282
10.0	0.97953	0.4898	0.2449	0.1224	0.2449	20	0.45276	0.2664	0.1132	0.0566	0.1132
15.0	0.55856	0.2793	0.1396	0.0698	0.1396	25	0.38592	0.1929	0.0965	0.0482	0.0965
20.0	0.24604	0.1230	0.0615	0.0308	0.0615	30	0.31747	0.1587	0.0794	0.0397	0.0794
25.0	0.08213	0.0411	0.0205	0.0103	0.0205	35	0.25204	0.1260	0.0630	0.0315	0.0630
30.0	0.02047	0.0102	0.0051	0.0026	0.0051	40	0.19310	0.0965	0.0483	0.0241	0.0483
35.0	0.00377	0.0019	0.0009	0.0005	0.0009	45	0.14277	0.0714	0.0357	0.0178	0.0357
40.0	0.00051	0.0002	0.0001	0.0001	0.0001	50	0.10187	0.0509	0.0255	0.0127	0.0255
						55	0.07013	0.0351	0.0175	0.0088	0.0175
						60	0.04659	0.0233	0.0116	0.0058	0.0116
						65	0.02987	0.0149	0.0075	0.0037	0.0075
						70	0.01847	0.0092	0.0046	0.0023	0.0046
						75	0.01102	0.0055	0.0028	0.0014	0.0028
						80	0.00635	0.0032	0.0016	0.0008	0.0016

TABLE 1.—(*Continued*)

x Meters	t = 100 Years					y Meters	t = 1 Year				
	$P_x + P_x'$	*oa* 0.37672	*eb* 0.18836	*fc* 0.12244	*gd* 0.24488		$P_y + P_y'$	*og* 0.37672	*ad* 0.24488	*bc* 0.12244	*ef* 0.18836
		$y = 0$, $z = 0$	$y = 0$, $z = n$	$y = m$, $z = n$	$y = m$, $z = 0$			$x = 0$, $z = 0$	$x = l$, $z = 0$	$x = l$, $z = n$	$x = 0$, $z = n$
0	0.18450	0.0695	0.0348	0.0266	0.0452	00	2.00000	0.7534	0.4898	0.2449	0.3767
5	0.18419	0.0694	0.0347	0.0225	0.0451	60	2.00000	0.7534	0.4898	0.2449	0.3767
10	0.18327	0.0690	0.0345	0.0224	0.0449	65	1.99995	0.7534	0.4897	0.2449	0.3767
15	0.18174	0.0685	0.0342	0.0222	0.0445	70	1.99949	0.7533	0.4896	0.2448	0.3766
20	0.17963	0.0677	0.0338	0.0220	0.0440	75	1.99623	0.7520	0.4888	0.2444	0.3760
25	0.17695	0.0667	0.0333	0.0217	0.0433	80	1.97953	0.7457	0.4848	0.2424	0.3729
30	0.17373	0.0654	0.0327	0.0213	0.0425	85	1.91782	0.7225	0.4696	0.2348	0.3612
35	0.17001	0.0640	0.0320	0.0208	0.0416	90	1.75345	0.6606	0.4294	0.2147	0.3303
40	0.16579	0.0625	0.0312	0.0203	0.0406	95	1.43767	0.5416	0.3521	0.1760	0.2708
45	0.16114	0.0607	0.0304	0.0197	0.0395	100	1.00000	0.3767	0.2449	0.1224	0.1884
50	0.15611	0.0588	0.0294	0.0191	0.0382	105	0.56233	0.2118	0.1377	0.0688	0.1059
55	0.15072	0.0568	0.0284	0.0184	0.0369	110	0.24655	0.0929	0.0604	0.0302	0.0464
60	0.14504	0.0546	0.0273	0.0178	0.0355	115	0.08218	0.0310	0.0201	0.0101	0.0155
65	0.13911	0.0524	0.0262	0.0170	0.0341	120	0.02047	0.0077	0.0050	0.0025	0.0039
70	0.13297	0.0501	0.0250	0.0163	0.0326	125	0.00377	0.0014	0.0009	0.0005	0.0007
75	0.12669	0.0477	0.0239	0.0155	0.0310	130	0.00051	0.0002	0.0001	0.0001	0.0001
80	0.12029	0.0453	0.0227	0.0147	0.0295	135	0.00005	0.0000	0.0000	0.0000	0.0000
85	0.11384	0.0429	0.0214	0.0139	0.0279	140	0.00000				
90	0.10737	0.0404	0.0202	0.0132	0.0263						
95	0.10092	0.0380	0.0190	0.0124	0.0247						
100	0.09457	0.0356	0.0178	0.0116	0.0232						

is, $oa = l$, $og = m$, $oe = n$. As previously explained, the values of the products of the two bracket factors are always less than one and, as shown also by the tabulations, the values of v/v_o along the axes always exceed those along lines parallel to the axes.

The values of v/v_o along the axes are shown in Figs. 2, 3, 4 for time intervals of 1, 9 and 100 yr. (columns *oa*, *og*, *oe* of Table 1). For 1000 years, $v/v_o = 0.0084$ at the origin of coordinates, the center of the intrusive body, so that there is still a remnant of the original heat within the mass. The existing temperatures are found by multiplying the tabular values of v/v_o by some assumed value of v_o, usually something like 600° or 1000°C.

Isothermal Surfaces

The condition for an isothermal surface is v/v_o = constant. To construct the surface, let Eq. 1 be written for large values of z in the abbreviated form,

$$\frac{2}{\sqrt{\pi}}\int_0^{\frac{n-z}{2\sqrt{\kappa t}}} e^{-\gamma^2}d\gamma = \frac{8v/v_o}{[P_x + P_x'][P_y + P_y']} - 1 \qquad [4]$$

When v/v_o is known, the value of z can be obtained from the inverse of the probability integral in Eq. 4. Using the values of $[P_x + P_x']$ and $[P_y + P_y']$ contained in Table 1, the values of the coefficients of v/v_o in Eq. 4 are easily computed. These coefficients are tabulated in Tables 2*a* and 3*a* for the respective time intervals of 1 and 9 yr., for the use of those who wish to calculate isothermal surfaces for the intrusive discussed here. The values of the first term on the right of the equality sign in Eq. 4 must fall between limits 1 and 2.

Table 1.—(*Continued*)

y Meters	$P_y + P_y'$	t = 9 Years				y Meters	$P_y + P_y'$	t = 100 Years			
		og 0.15034	*ad* 0.14005	*bc* 0.07002	*ef* 0.07517			*og* 0.04612	*ad* 0.04582	*bc* 0.02291	*ef* 0.02306
		$x = o$, $z = o$	$x = l$, $z = o$	$x = l$, $z = n$	$x = o$, $z = n$			$x = o$, $z = o$	$x = l$, $z = o$	$x = l$, $z = n$	$x = o$, $z = n$
0	1.99978	0.3007	0.2801	0.1400	0.1503	0	1.50690	0.0695	0.0690	0.0345	0.0348
10	1.99949	0.3006	0.2800	0.1400	0.1503	10	1.50056	0.0692	0.0688	0.0344	0.0346
20	1.99800	0.3004	0.2798	0.1399	0.1502	20	1.48171	0.0683	0.0679	0.0339	0.0342
30	1.99315	0.2997	0.2791	0.1396	0.1498	30	1.45074	0.0669	0.0665	0.0332	0.0335
40	1.97953	0.2976	0.2772	0.1386	0.1488	40	1.40837	0.0650	0.0645	0.0323	0.0325
50	1.94655	0.2926	0.2726	0.1363	0.1463	50	1.35549	0.0625	0.0621	0.0310	0.0313
60	1.87766	0.2823	0.2630	0.1315	0.1412	60	1.29327	0.0596	0.0592	0.0296	0.0298
70	1.75345	0.2636	0.2456	0.1228	0.1318	70	1.22303	0.0564	0.0560	0.0280	0.0282
80	1.56019	0.2346	0.2185	0.1092	0.1173	80	1.14627	0.0529	0.0525	0.0263	0.0264
90	1.30069	0.1956	0.1822	0.0911	0.0978	90	1.06456	0.0491	0.0488	0.0244	0.0246
95	1.15314	0.1734	0.1615	0.0808	0.0867	100	0.97953	0.0452	0.0449	0.0224	0.0226
100	1.00000	0.1504	0.1400	0.0700	0.0752	110	0.89279	0.0412	0.0409	0.0204	0.0206
105	0.84686	0.1273	0.1186	0.0593	0.0637	120	0.80594	0.0372	0.0369	0.0185	0.0186
110	0.69931	0.1051	0.0979	0.0490	0.0526	130	0.72042	0.0332	0.0330	0.0165	0.0166
115	0.56233	0.0845	0.0788	0.0394	0.0423	140	0.63858	0.0294	0.0293	0.0146	0.0147
120	0.43981	0.0661	0.0616	0.0308	0.0331	150	0.55856	0.0258	0.0256	0.0128	0.0129
125	0.33422	0.0503	0.0468	0.0234	0.0251	160	0.48430	0.0223	0.0222	0.0111	0.0112
130	0.24655	0.0371	0.0345	0.0173	0.0185	170	0.41553	0.0192	0.0190	0.0095	0.0096
135	0.17641	0.0265	0.0247	0.0124	0.0133	175	0.38337	0.0177	0.0176	0.0088	0.0088
140	0.12234	0.0184	0.0171	0.0086	0.0092	180	0.35274	0.0163	0.0162	0.0081	0.0081
145	0.08218	0.0124	0.0115	0.0058	0.0062	185	0.32368	0.0149	0.0148	0.0074	0.0075
150	0.05345	0.0080	0.0075	0.0037	0.0040	190	0.29622	0.0137	0.0136	0.0068	0.0068
155	0.03364	0.0051	0.0047	0.0024	0.0025	195	0.27034	0.0125	0.0124	0.0062	0.0062
160	0.02047	0.0031	0.0029	0.0014	0.0015	200	0.24604	0.0114	0.0113	0.0056	0.0057
165	0.01205	0.0018	0.0017	0.0008	0.0009	205	0.22331	0.0103	0.0102	0.0051	0.0052
170	0.00685	0.0010	0.0010	0.0005	0.0005	210	0.20210	0.0093	0.0093	0.0046	0.0047

TABLE 1.—(*Continued*)

z Meters	$P_z + P_z'$	t = 1 Year			
		oe 0.37673	*ab* 0.24488	*dc* 0.12244	*gf* 0.18836
		$x = o$, $y = o$	$x = l$, $y = o$	$x = l$, $y = m$	$x = o$, $y = m$
0	2.00000	0.7534	0.4898	0.2449	0.3767
960	2.00000	0.7534	0.4898	0.2449	0.3767
965	1.99995	0.7534	0.4898	0.2449	0.3767
970	1.99949	0.7533	0.4896	0.2448	0.3766
975	1.99623	0.7520	0.4888	0.2444	0.3760
980	1.97953	0.7457	0.4848	0.2424	0.3729
985	1.91782	0.7225	0.4696	0.2348	0.3613
990	1.75345	0.6606	0.4294	0.2147	0.3303
995	1.43767	0.5416	0.3521	0.1760	0.2708
1,000	1.00000	0.3767	0.2449	0.1224	0.1884
1,005	0.56233	0.2118	0.1377	0.0689	0.1059
1,010	0.24655	0.0929	0.0604	0.0302	0.0464
1,015	0.08218	0.0310	0.0201	0.0101	0.0155
1,020	0.02047	0.0077	0.0050	0.0025	0.0039
1,025	0.00377	0.0014	0.0009	0.0005	0.0007
1,030	0.00051	0.0002	0.0001	0.0001	0.0001
1,035	0.00005	0.0000	0.0000	0.0000	0.0000
1,040	0.00000	0.0000	0.0000	0.0000	0.0000

z Meters	$P_z + P_z'$	t = 9 Years			
		oe 0.15033	*ab* 0.14003	*dc* 0.07002	*gf* 0.07517
		$x = o$, $y = o$	$x = l$, $y = o$	$x = l$, $y = m$	$x = o$, $y = m$
0	2.00000	0.3007	0.2801	0.1401	0.1504
900	1.99989	0.3006	0.2800	0.1400	0.1503
920	1.99800	0.3004	0.2798	0.1399	0.1502
940	1.97953	0.2976	0.2772	0.1386	0.1488
945	1.96636	0.2956	0.2754	0.1377	0.1478
950	1.94655	0.2926	0.2726	0.1363	0.1463
955	1.91782	0.2883	0.2686	0.1343	0.1442
960	1.87766	0.2823	0.2629	0.1315	0.1412
965	1.82359	0.2741	0.2554	0.1277	0.1371
970	1.75345	0.2636	0.2455	0.1228	0.1318
975	1.66578	0.2504	0.2333	0.1166	0.1252
980	1.56019	0.2345	0.2185	0.1093	0.1173
985	1.43767	0.2161	0.2013	0.1007	0.1081
990	1.30069	0.1955	0.1821	0.0911	0.0978
995	1.15314	0.1734	0.1615	0.0808	0.0867
1,000	1.00000	0.1503	0.1400	0.0700	0.0752
1,005	0.84686	0.1273	0.1186	0.0593	0.0637
1,010	0.69931	0.1051	0.0979	0.0490	0.0526
1,015	0.56233	0.0845	0.0787	0.0394	0.0423
1,020	0.43981	0.0661	0.0616	0.0308	0.0331
1,025	0.33422	0.0502	0.0468	0.0234	0.0251
1,030	0.24655	0.0371	0.0345	0.0173	0.0185
1,035	0.17641	0.0265	0.0247	0.0214	0.0133
1,040	0.12234	0.0184	0.0171	0.0086	0.0092
1,045	0.08218	0.0124	0.0115	0.0058	0.0062
1,050	0.05345	0.0080	0.0075	0.0037	0.0040

TABLE 1.—(*Continued*)

z Meters	$P_z + P_z'$	t = 100 Years			
		oe 0.03475	*ab* 0.03452	*dc* 0.02244	*gf* 0.02259
		$x = o$, $y = o$	$x = l$, $y = o$	$x = l$, $y = m$	$x = o$, $y = m$
0	2.00000	0.0695	0.0690	0.0449	0.0452
600	2.00000	0.0695	0.0690	0.0449	0.0452
650	1.99995	0.0695	0.0690	0.0449	0.0452
700	1.99949	0.0695	0.0690	0.0449	0.0452
750	1.99623	0.0694	0.0689	0.0448	0.0451
800	1.97953	0.0688	0.0683	0.0444	0.0447
850	1.91782	0.0666	0.0662	0.0430	0.0433
900	1.75345	0.0609	0.0605	0.0394	0.0396
950	1.43767	0.0500	0.0496	0.0323	0.0325
1,000	1.00000	0.0348	0.0345	0.0224	0.0226
1,050	0.56233	0.0195	0.0194	0.0126	0.0127
1,100	0.24655	0.0086	0.0085	0.0055	0.0056
1,150	0.08218	0.0029	0.0028	0.0018	0.0019
1,200	0.02047	0.0007	0.0007	0.0005	0.0005
1,250	0.00377	0.0001	0.0001	0.0001	0.0001

Tables 2*b* and 3*b* give the values of z respectively for $v/v_0 = 0.4$, $t = 1$ yr.; and $v/v_0 = 0.2$, $t = 9$ yr. The results for the first case are shown graphically in Fig. 5 and the limiting coordinates are indicated roughly in Tables 2*b* and 3*b*.

TABLE 2.—*Isothermal Surface*

x	$y =$ 0000	$y =$ 6000	$y =$ 6500	$y =$ 7000	$y =$ 7500	$y =$ 8000	$y =$ 8500	$y =$ 9000	$y =$ 9500	$y =$ 10,000
a. Values of coefficients of v/v_0 for an intrusive body 2000 by 20,000 by 200,000 cm. $\kappa = 0.0118$, $k = 0.0042$, $t = 1$ year										
000	2.6545	2.6545	2.6545	2.6551	2.6595	2.6819	2.7682	3.0277	3.6927	5.3089
250	2.7253	2.7253	2.7254	2.7261	2.7305	2.7535	2.8421	3.1086	3.7913	5.4507
500	2.9510	2.9510	2.9510	2.9517	2.9565	2.9815	3.0774	3.3659	4.1052	5.9019
750	3.3745	3.3745	3.3746	3.3754	3.3809	3.4094	3.5191	3.8490	4.6944	6.7490
1,000	4.0836	4.0836	4.0837	4.0846	4.0913	4.1258	4.2586	4.6578	5.6808	8.1672
1,250	5.2429	5.2429	5.2431	5.2443	5.2529	5.2972	5.4676	5.9802	7.2937	10.486
1,500	7.1613	7.1613	7.1615	7.1631	7.1748	7.2353	7.4681	8.1682	9.9624	14.323
1,750	10.434	10.434	10.434	10.437	10.454	10.542	10.881	11.901	14.515	20.868
2,000	16.258	16.258	16.258	16.262	16.288	16.426	16.954	18.543	22.617	32.515
2,250	27.152	27.152	27.153	27.159	27.203	27.433	28.316	30.969	37.771	54.304
b. Values of z (cm.) for $v/v_0 = 0.4$, $t = 1$ year										
000	99,933	99,933	99,933	99,933	99,931	99,921	99,884	99,769	99,449	
250	99,902	99,902	99,902	99,902	99,900	99,890	99,851	99,732	99,395	
500	99,803	99,803	99,803	99,803	99,801	99,790	99,747	99,613	99,207	
750	99,609	99,609	99,609	99,608	99,606	99,592	99,538	99,363	98,666	
1,000	99,221	99,221	99,221	99,220	99,216	99,193	99,099	98,716		
1,250										

TABLE 3.—*Isothermal Surface*

x	$y =$ 0000	$y =$ 1000	$y =$ 2000	$y =$ 3000	$y =$ 4000	$y =$ 5000	$y =$ 6000	$y =$ 7000	$y =$ 8000	$y =$ 9000
a. Values of coefficients of v/v_0 for an intrusive body 2000 by 20,000 by 200,000 cm. $k = 0.0118$, $k = 0.0042$, $t = 9$ years										
000	6.6521	6.6531	6.6580	6.6742	6.7201	6.8340	7.0847	7.5866	8.5263	10.227
500	6.7711	6.7721	6.7771	6.7936	6.8403	6.9563	7.2115	7.7223	8.6789	10.410
1,000	7.1412	7.1423	7.1476	7.1650	7.2143	7.3365	7.6056	8.1444	9.1533	10.980
1,500	7.8036	7.8047	7.8106	7.8295	7.8834	8.0170	8.3112	8.8999	10.002	11.998
2,000	8.8357	8.8369	8.8436	8.8651	8.9261	9.0773	9.4103	10.077	11.325	13.585
2,500	10.366	10.368	10.375	10.400	10.472	10.649	11.040	11.822	13.287	15.938
3,000	12.601	12.603	12.612	12.643	12.730	12.946	13.421	14.371	16.151	19.374
3,500	15.872	15.875	15.886	15.925	16.035	16.306	16.904	18.102	20.344	24.403
4,000	20.717	20.720	20.736	20.786	20.929	21.283	22.064	23.627	26.554	31.852
4,500	28.020	28.024	28.046	28.114	28.307	28.786	29.843	31.957	35.915	43.080
b. Values of z (cm.) for $v/v_0 = 0.2$, $t = 9$ years										
000	98,895	98,895	98,891	98,879	98,847	98,764	98,579	98,183	97,287	
500	98,810	98,809	98,806	98,794	98,760	98,675	98,482	98,068	97,110	
1,000	98,536	98,535	98,531	98,518	98,480	98,385	98,167	97,684	96,442	
1,500	97,998	97,997	97,992	97,975	97,927	97,805	97,518	96,825		
2,000	96,911	96,910	96,901	96,872	96,788	96,565	95,952			

Interpretation of the Calculations

A very significant result suggested by these calculations is the rapid changes in gradient in a relatively thin outer zone of the intrusive corresponding to the part of the intrusive that is outside the "dead line" (Fig. 1). Such rapid cooling probably results in developing a highly fractured zone in which supersaturated solutions from great depths may deposit various metals. Another very significant result is the very small change in the temperature gradients within the "dead line" (Figs.

3, 4). It seems rather improbable that cooling under these conditions would induce fracturing of the rocks. This condition does not exist for the x axis as shown in Fig. 2, for the thickness of the intrusive in this direction is very small. For large intrusives, however, the type of temperature curve represented in Figs. 3 and 4 must apply in each of the three coordinate directions.

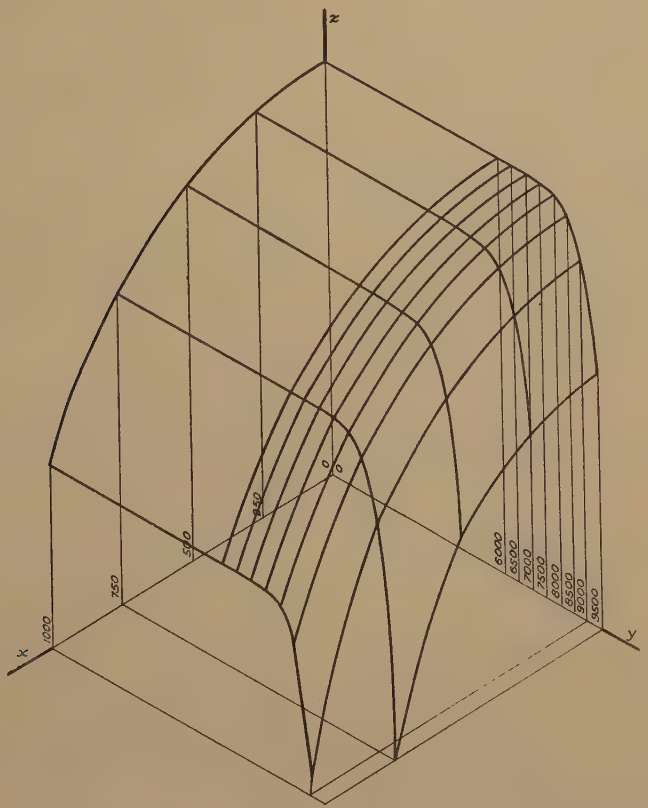


FIG. 5.—ISOTHERMAL SURFACE FOR $v/v_0 = 0.4$, $t = 1$ YEAR (TABLE 2b). The z coordinate is the value given in Table 2b—98,666 cm. The scales along the three axes are not the same.

The time required to cool small igneous bodies is very small in relation to geological time. Thus for a cube 200 by 200 by 200 meters (656.16 ft.), $v/v_0 = 0.0234$ at the center of the intrusive when $t = 1000$ yr., but for a cube 2000 by 2000 by 2000 meters (1.24 mile) the values at the center ($x = 0$, $y = 0$, $z = 0$) for different time intervals are as follows:

v/v_0	t
0.99925	1,000 yr.
0.4277	10,000 yr.
0.0234	100,000 yr.
0.00079	1,000,000 yr.

CONCLUSIONS

By assigning different values to v/v_0 in Tables 2a and 3a, it is easy to show that the distances between the isothermal surfaces increase very slowly until a point near the surface, probably the "dead

line," is reached, after which the isotherms separate quite rapidly; also, it is well known that the distance between the isotherms is a minimum in the valleys and a maximum over the tops of ridges and domes.[4-7] Hence, summarizing our results, we may say that the spreading of the isotherms is a favorable condition for the deposition of metals as far as increased tendency toward fracturing is in itself a favoring condition. This condition prevails in the cupolas,[4-7] and, as just stated, in the outer shell of the intrusive beyond the "dead line." The concentration of the isotherms beneath the troughs of the intrusive is a much less favorable condition for the deposition of metals.

The processes of cooling discussed in this paper may have important applications in hot-spring areas. A body of sufficient size, say 1 cu. mile, would be a source of considerable quantities of excess heat, certainly for tens of thousands of years.

After the lapse of a few thousand years, small intrusions (Figs. 2, 3, 4) could not be detected by the rise in temperature as the intrusives were approached. On the other hand, intrusives whose dimensions were of the order of many cubic miles would show a rise in temperature in all directions as they were approached, even after the lapse of one or more million years.

References

1. W. H. Emmons: On the Mechanism of the Deposition of Certain Metalliferous Lode Systems Associated with Granitic Batholiths. Ore Deposits of the Western States (Lindgren Volume), A.I.M.E., 330. New York, 1933.
2. L. R. Ingersoll and O. J. Zobel: An Introduction to the Mathematical Theory of Heat Conduction with Engineering and Geological Applications, 146–148. Boston, 1913. Ginn and Co. (Out of print.)
3. T. S. Lovering: Theory of Heat Conduction Applied to Geological Problems. *Bull.* Geol. Soc. Amer. (1935) **46**, 87–93. (Graphical methods of calculation are developed in this paper.)
4. C. H. Lees: On the Shapes of the Isogeotherms under Mountain Ranges in Radioactive Districts. *Proc.* Roy. Soc. London (1900) **A-83**, 339–346.
5. H. Jeffreys: The Distribution of Temperature Gradient in the Earth's Crust by Inequalities of Height. Monthly Notices, Royal Astronomical Soc., Geophysical Supplement (1938) 360–362.
6. C. E. Van Orstrand: Some Possible Applications of Geothermics to Geology. *Bull.* Amer. Assn. Petr. Geol. (1934) **18**, 16–17.
7. C. E. Van Orstrand: On the Correlation of Isogeothermal Surfaces with the Rock Strata. *Physics* (1932) **2**, 143–147.

DISCUSSION

A. C. Lane.*—The mathematical curves in Van Orstrand's interesting paper closely parallel some of mine[8] in studying the effect of cooling upon the grain of the lavas and the deposition of copper, and are practically identical.

The main theoretical, mathematical difference is that I assumed an exterior deadline outside the heated contact zone in which the temperature did not change. Van Orstrand's curves soon drop to so near that temperature that assuming no change can obviously make but little difference.

There is, however, a reason why my curves might theoretically approach more nearly the actual conditions, which may also be practically important—and that is that the heat may actually be absorbed by chemical or physical conditions, such as exposure to atmospheric or underground circulation or the absorption of heat by the specific heat of water in its evaporation into steam or other chemical reactions.

Also within the intrusive, when we get to the zone of constant grain, we approach an interior deadline in which the cooling or loss of volatiles, other than certain mineralizers, comes so long after the intrusion that the rate of loss, at a given temperature, not time, which might be that of becoming, though hot, highly viscous, and a practically solid glass able to crack under earthquake shock, quite possibly with considerable crystallization of the constituents (Grout's "mush"); when the heat flow is no longer dependent appreciably upon the distance from the margin.

It is within this zone that volatile transfer emphasized by T. A. Broderick may obtain most of its load. There is thus good, theoretical

* Geologist, Cambridge, Massachusetts.

[8] See Mich. Geol. Survey (1895) **6** and *Pub.* No. 6 (1911); also E. Fairbanks: Laboratory Investigation of Ores, 120.

ground for what is practically observed—an interior and exterior contact zone.

If the initial temperature is less than as much again above this consolidation temperature as that is above the difference between the consolidation rock temperature and the country rock temperature, there will be no chilled zone of finer grain and plenty of time for loss of volatile near the contact. This seems to be true for granites. On the other hand, if there is a finer interior contact zone, there will be more time for volatile transfer and loss farther in and the more, the hotter the intrusive.

Thus the margin may or may not be in the belt of volatile transfer longer than the center.

Now here is a way to check up and find out some interesting things about ore deposits. The lead in the earlier formed minerals that could lead or combine it as a crystallize, will have a lead which will have less of the isotopes which are the more slowly added by disintegration of U 238 and TH 232, than the lead which occurs in minerals which take into their framework more willingly the radioactive elements from whose disintegration these more slowly formed isotopes come.

That will also be true of the volatilized lead, if it goes off by itself to be precipitated in a gold quartz vein which has little radioactivity in the gangue. A number of recent papers indicate that quartz is, in general, very low in radioactivity.

For instance, the galena from Casapalca, Peru, has but 18.86 parts of Pb206 and 38.75 parts of Pb208 to 22.3 respectively 41.8 in the galena of Joplin.[9]

It is a "hunch" that the former has been derived from a source which had less radioactivity, such as the deep basaltic layer, while the latter might have been volatized from a zircon syenite or a granite. There are other possible explanations, and it is worth while to remember that the diffusion of volatiles, which T. M. Broderick has recently emphasized, may follow the same laws as the diffusion of caloric.

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[9] See report of the Committee on the Measurement of Geologic Time, 1942, p. 28, and also notice to reference to Russell's paper on p.33.

A Field Method for Determining the Magnetic Susceptibility of Rocks

By R. C. Hyslop

(New York Meeting, February 1941)

The object of this experiment was to obtain a usable set of field curves for determining the susceptibility of rocks with the vertical magnetometer. The need often arises for determining the susceptibility of rocks in the field in order to interpret magnetic anomalies obtained. This is particularly true when diamond drilling has been done and the relation to the surface rocks of the samples taken is desired. Many methods of measuring rock susceptibility have been developed, but in general they require careful shaping of the sample or pulverizing it in addition to delicate laboratory measuring instruments designed for the purpose.

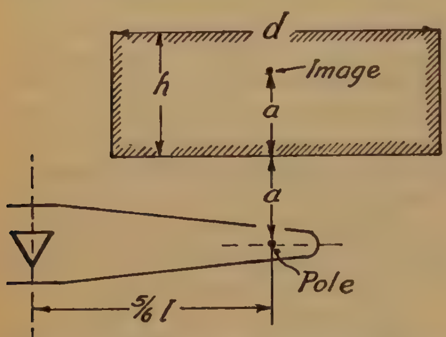

Fig. 1.—Arrangement of specimen with reference to vertical magnetometer system, for susceptibility determination.

The requirements for a practical method for the determination of susceptibilities are as follows:

1. There should be as little alteration as possible of the specimen.
2. A minimum of time should be required in the preparation of the specimen and the calibration of the equipment.
3. Theequipment used should be portable.
4. An accuracy within the limits of the survey at hand should be obtainable.
5. A means of measuring the remnant magnetism should be available.

Laboratory Procedure

With these ideas in mind, the problem was approached in the manner in which Koenigsberger[1] developed his method using the principle of the electrical theory of images of Lord Kelvin and applying it to the magnetic case. This solution of the problem states that the apparent change in the magnetic field intensity ΔZ due to the proximity of a specimen is given by:

$$\Delta Z = \frac{\pi m k}{2a^2}$$

Where k is the susceptibility of the specimen, m the strength of the pole of the needle, and a its distance from the surface of the specimen, as shown in Fig. 1.[2] This relation is true only for an infinite body and corrections are necessary for a finite body.

Koenigsberger used in his work a variometer of special design. He suggested that a Schmidt vertical balance or horizontal magnetometer, as well as some other instrument, might be used. The Colorado School of Mines horizontal torsion magnetometer operates on this principle. In the

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[1] References are at the end of the paper.

work herein described it was decided to use the Schmidt vertical magnetometer, as it is widely used in field work and fills the requirements of portability and accuracy mentioned previously.

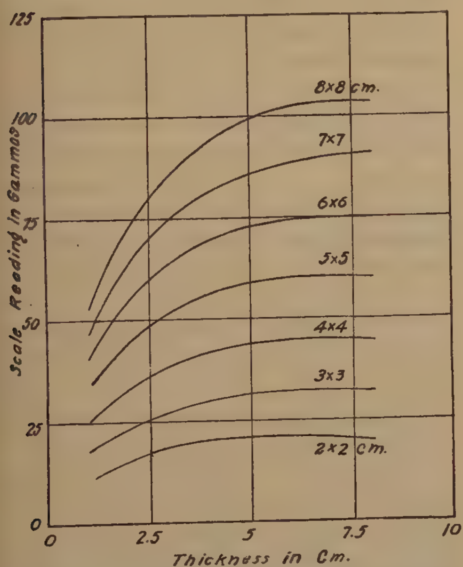

FIG. 2.—VARIATION IN READING WITH AREA AND THICKNESS FOR SUSCEPTIBILITY OF 6.67×10^{-4}.

A new and it is believed a more practical approach to the corrections of Koenigsberger was tried. The deflection of the system of a Schmidt vertical magnetometer was obtained when a sample was held close to one pole. By application of the dimensions of the specimen to a set of curves obtained by measuring deflections for samples of known susceptibility with known dimensions, the susceptibility of the specimen may be obtained directly. The value of such a set of curves to the geophysicist in the field is easily seen.

To obtain a standard of known susceptibility, which would be easy to shape to the desired size, it was decided to use a mixture of fine iron filings in modeling clay, thus simulating a rock with any desired susceptibility. This also gave the opportunity to obtain samples over the entire range of susceptibilities of rocks found in nature, by the use of different amounts of filings. For this particular experiment, five concentrations of filings were used, ranging from low to high values of susceptibilities.

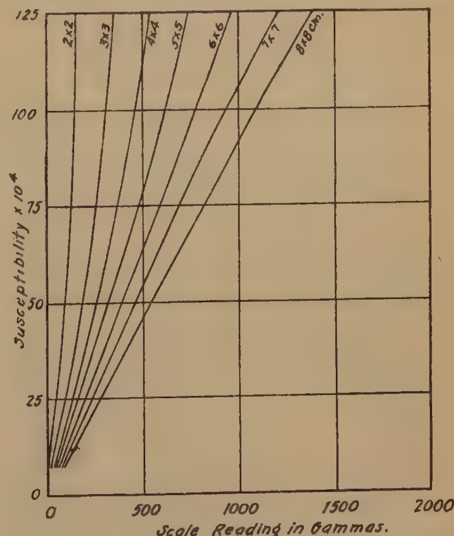

FIG. 3.—VARIATION IN READING AND SUSCEPTIBILITY FOR THICKNESS OF 2 CENTIMETERS.

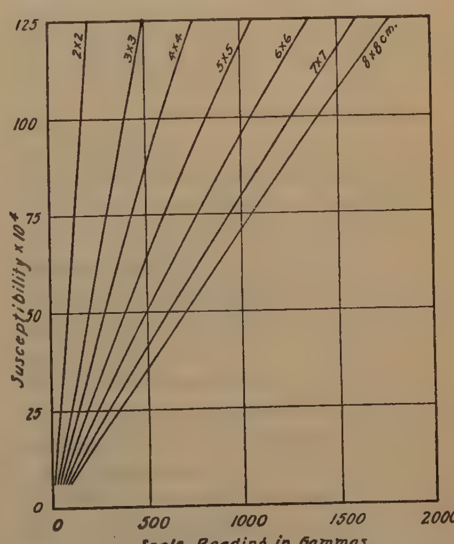

FIG. 4.—VARIATION IN READING AND SUSCEPTIBILITY FOR THICKNESS OF 4 CENTIMETERS.

The samples were cut into blocks with plane surfaces, with different thicknesses and square cross sections. The greatest

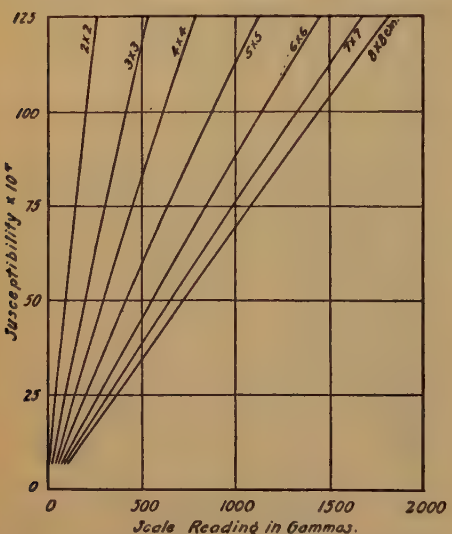

FIG. 5.—VARIATION IN READING AND SUSCEPTIBILITY FOR THICKNESS OF 6 CENTIMETERS.

thickness used was 8 cm. and the least was 1 cm. The areas ranged from squares 8 cm. on a side to 2 cm. on the side, for all susceptibilities. Each specimen was placed over the south pole of the magnetometer (use of the other pole being impossible, in the particular instrument used, on account of the level bubble). A reading was recorded in four orientations, turning the specimen 90° between readings, with each end of the block resting on the instrument casing. The multiple readings were taken to offset any effect of remnant magnetism or permanent magnetism of the specimen.

The susceptibility of the five standards used was obtained by comparison with a solution of ferric chloride of known concentration. In this case a 50 per cent solution was used and applied to the formula $k = \{88.00p - 0.78(1 - p)\}10^{-6}$ (where p = concentration of solution and k = mass susceptibility). The susceptibility of the clay samples was then obtained by the following method:

Several copper vessels of square cross section were made so that a section the same as that of the clay sample was available, the thickness of which could be varied by changing the depth of the ferric chloride in the vessel. Readings were taken with various areas and thicknesses. The value of the field caused by the insertion of the clay sample was compared with that obtained by the use of the known susceptibility of the ferric chloride solution. The susceptibility was then calculated by using the ratio of the two readings. The

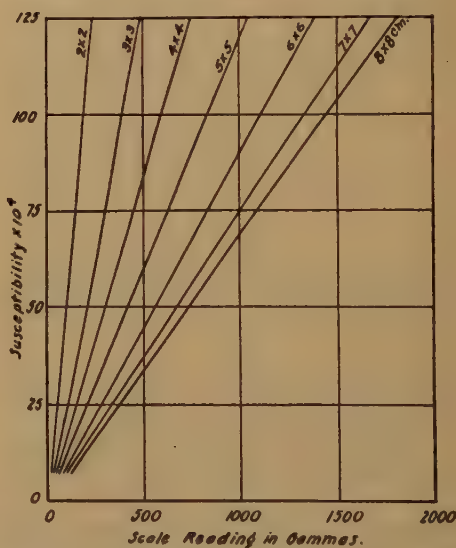

FIG. 6.—VARIATION IN READING AND SUSCEPTIBILITY FOR THICKNESS OF 8 CENTIMETERS.

susceptibility was determined in the same manner for all the calibration specimens.

A set of curves was drawn plotting scale readings in gammas against thickness to smooth out the recorded values in order to get a closer check on any individual point. Fig. 2 illustrates a typical family of curves so obtained, and the variation with thickness and cross section for a sample with a value of susceptibility of 667×10^{-6}. Susceptibilities obtained from the readings of these curves checked very closely for various thicknesses and areas.

The Field Curves

Curves were then plotted with susceptibility as ordinate and scale reading in gammas as abscissa for each cross section, thus obtaining a family of curves for each thickness. Curves for thicknesses of 2, 4, 6 and 8 cm. are shown (Figs. 3, 4, 5, 6). They are now ready to be used in the field for obtaining the susceptibility of a rock sample.

To use this method in the field a sample is selected and shaped roughly in the form of a parallelopiped with nearly square sections and applied to the magnetometer. Readings should be taken in four different positions with one end of the sample down, then four more readings with the sample reversed, rotating the specimen 90° between readings. The value in gammas is obtained by multiplying the average of the readings by the scale value of the magnetometer. On the graph corresponding to the thickness of the sample the value in gammas is traced up from the abscissa to the intersection with the curve corresponding to the cross section of the sample. The susceptibility is then read directly from the ordinate.

In the application to the rock specimens in the field, it is best to use those in the higher range of thicknesses, if possible, as can be seen by examination of curves. These curves show that the variation of the field is very much less for changes of thickness in this range than in the thinner specimens. For fractional thicknesses not falling on the curves, a very close value can be obtained by interpolating on the field curves for the thicknesses used.

As indicated by the results shown here, this method is reliable within the accuracy of most surveys. Also, such a set of curves would be invaluable to the geophysicist in the field in saving time and in the interpretation of the results obtained.

References

1. J. G. Koenigsberger: Method of Measuring the Susceptibility of Rocks. *Terrestrial Magnetism and Atmospheric Electricity* (Sept. 1929) 34, 210. Another equation of similar character relating mass susceptibility and percentage of iron chloride solution is in Smithsonian Tables, Ed. 8, 475. 1933.

2. C. A. Heiland: Geophysical Exploration, 302. New York, 1940. Prentice-Hall.

DISCUSSION

(*Sherwin F. Kelly presiding*)

S. F. Kelly.*— You say that you can obtain the values of other sizes by interpolation. I see how that would work quite nicely as between 4 by 4 and 5 by 5. Suppose you have 4 by 6, will it be half way between?

C. A. Heiland.†—No. The effect is proportional to the area. If there is a great number of oblong samples, you can easily set up another diagram. The present diagram was made only for square specimens, for the sake of convenience.

Member.—Would it be possible to have some sort of graticule, by which one could calculate the effect for a specimen of any shape?

C. A Heiland.—The present diagram is based on what is mostly used in practice, but there is no limitation to it as far as graphic means are concerned.

Member.—I was thinking about the difficulty of trimming some type of specimens to that size and shape.

C. A. Heiland.—It is not necessary to have an absolutely flat surface, or an absolutely smooth edge. The corrections are not very large, but they are still important enough to require these diagrams in going, for instance, from 2 by 2 to 8 by 8, or something like that.

S. F. Kelly.—I wonder what would happen if you had a chunk such as the meticulous geologist likes to make out of his specimens. You do not have a definite thickness, but it is a lenticular shape.

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* Sherwin F. Kelly Geophysical Services, Inc., Wilmington, Del.; Geophysical Explorations Ltd., Toronto, Ont., Canada.

† Heiland Research Corporation, Denver, Colo., and Professor of Geophysics, Colorado School of Mines, Golden, Colorado. Dr Heiland presented Mr. Hyslop's paper.

C. A. Heiland.—I believe I discussed the treatment of such specimens at the 1931 meeting. It has nothing to do with the method discussed in Hyslop's paper, but has the advantage of being applicable to any kind of specimen. As the magnetic effect depends on the shape of the specimen, it is but necessary to make a cast of it from a material of known susceptibility, and to compare the two by the solenoid method, using an astatic or similar magnetometer. The deflection will give the ratio of the two susceptibilities.

An important thing to remember about the method discussed in Hyslop's paper is this: The thicker the specimen, the smaller is the correction for differences in thickness, as the other surface is less effective in modifying the strength of the original image.

Determination of Magnetic Susceptibilities of Rocks in Situ

By R. G. Paterson, Student Associate A.I.M.E.

(New York Meeting, February 1941)

The usual procedure in determining the magnetic susceptibilities of rocks and formations has been to take samples in the field and measure their volume susceptibilities in the laboratory, using one of numerous methods available. In none of these methods is the measuring instrument suited for field use.

Usually the sample is pulverized; sometimes it is machined to a desired size and shape, and in one method[1] a cast of the sample is made and the susceptibility of the rock compared with that of a material of known susceptibility of the same size and shape, made from the cast of the original sample.

Some writers assert that the difference in susceptibility of a rock sample in powdered and solid forms is negligible, and while doubtless this is true in many cases there are others in which the difference becomes appreciable. Further, the susceptibility of a small specimen may differ from that of the rock from which it is taken, owing to the stresses produced by the hammering or other forces used to obtain the sample and shape it for testing. Wilson[2] found that an individual specimen of granite had about the same susceptibility in the solid as in the powdered form, but that pieces from different parts of the rock varied as much as 750 per cent because of unequal distribution of magnetite.

The most accurate value of susceptibility would, obviously, be obtained from averaging a number of tests on the undisturbed rock instead of from one or two samples. No such procedures have been published, to the writer's knowledge. It is the purpose of this paper to describe a method by which susceptibilities of rocks may be determined in place by means of a portable instrument.

Method

The principle involved in this new method is that there is a change in inductance of a coil due to the presence in its magnetic field of a paramagnetic or diamagnetic medium. In this case, however, the windings of the coil do not enclose any part of the rock under test. Instead, the coil is circular, being small in cross section as compared to its radius, and consists of several hundred turns of fine wire. It is placed flat on the rock of which the susceptibility is to be measured. Thus only part of the magnetic field from the coil penetrates the rock under test. The relation between the change in field strength or inductance of the coil and the susceptibility of the medium will be developed later.

To measure the change in the inductance of the coil due to the presence of a magnetic material an alternating-current inductance bridge was chosen.

Description of Apparatus

Of many alternating-current bridge methods applicable,[3] the one shown in Fig. 1 (Owen's bridge[4]) was adopted for its simplicity and sensitivity.

In Fig. 1, the test coil is indicated by P_1L_1. It is connected to the bridge by about

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[1] References are at the end of the paper.

8 ft. of bifilar flexible wire. The coil is 9.4 cm. in mean diameter, contains 1000 turns of No. 31 enameled wire and has a resistance of 139.1 ohms. The cross-sectional

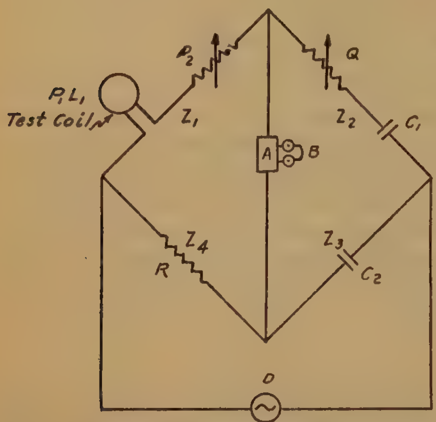

FIG. 1.—DIAGRAM OF OWEN'S INDUCTANCE BRIDGE (AS USED IN EXPERIMENTS).
P_1L_1, test coil; P_2 and Q, variable resistances.
C_1 and C_2, fixed standard condensers.
R, fixed standard resistance.
z_1, z_2, z_3, z_4, branch impedances.
A, amplifier; B, headphones; D, power source.

dimensions are 1 cm. by 0.5 cm. Accurately measured, its inductance was 0.17995 henrys.

If the coil is symmetrically wound in regular layers its inductance may be closely calculated by several formulas, for which but two references are given, Fleming[5] and Rosa.[6]

A coil of larger diameter than the one described is recommended for field work. A small coil was used for experimental work, to decrease the size of the samples needed. P_2 and Q are standard variable resistances reading up to 5000 ohms each. They should have verniers reading to at least 0.1 ohm. C_1 and C_2 are fixed standard condensers of 0.13 and 0.06 microfarad, respectively. As a frequency of 500 cycles was used and branch impedances of 5000 ohms, these values of capacity were calculated to give 5000-ohms impedance (see section on Experimental Work). The nearest values available were then used. R is a fixed standard resistance of 5000 ohms.

The source of current may be a buzzer, a maintained tuning fork, a motor-driven alternator, or a vacuum-tube oscillator. The first two both give a loud note and if used must be placed some distance away and in a soundproof box, so that the direct note will not be heard where headphones are used for detecting the point of balance on the bridge. A buzzer has a rather impure wave form. Motor-driven alternators give a satisfactory wave form and are suitable for low frequencies but usually are too cumbersome for field use. For frequencies above, say, 200 cycles, the vacuum-tube oscillator undoubtedly is best suited for precise tests. It gives an adequate output at steady frequency with a good wave form. A variable-frequency vacuum-tube oscillator was used in the experiments, so that the effects of different frequencies could be investigated.

Whatever the power source chosen, it is advisable to connect it to the bridge through a small transformer. By providing a grounded screen between the two windings of this transformer, capacity effects between the source and the bridge are minimized. It is also well to ground such parts as one side of the amplifier, for example, to make the whole instrument more stable. It was found that wiring all parts in such a manner as to reduce the internal capacities between wires and units improved the performance of the bridge.

For detecting the point of balance, headphones were used, connected through a two-stage transformer-coupled amplifier. Three stages of resistance coupling might be better, and a low-pass filter is recommended to cut out harmonics and give a better null point. With a constant-frequency source of not too high a value, a vibration galvanometer is satisfactory for determining the balance point. For field work, where such noises as those of wind or traffic make the use of headphones

impracticable, it might be necessary to use such a galvanometer. It can be obtained in very small sizes.

In using the bridge, balance is obtained by varying only the resistances P_2 and Q. This is not difficult, as the two adjustments for balance are independent of each other. In the circuit shown in Fig. 1, at balance:

$$z_1 z_3 = z_2 z_4$$

or

$$(P + j\omega L)\left(-\frac{j}{\omega C_2}\right) = \left(Q - \frac{j}{\omega C_1}\right) R \quad [1]$$

z = impedance; $j = \sqrt{-1}$, ω = frequency in radians per sec.; $P = P_1 + P_2$; L = self-inductance. Separating reals and imaginaries,

$$C_1 P = C_2 R \quad [2]$$

$$L = RQC_2 \quad [3]$$

In practice, the inductance of the test coil in air is first measured, and then its inductance when lying flat on the face of the rock whose susceptibility is to be determined. The difference of these two values is a measure of the susceptibility of the rock.

Theory

The relation between the change in inductance or flux of a coil and the permeability or susceptibility of a medium on which it is laid is somewhat complex. The writer knows of no article dealing directly with this subject. However, an outline of one method of determining this relation will be given, which is used in the calculation of magnetic fields in electrical machines. It involves the determination of the permeance* of electrical field paths and is referred to by Karapetoff.[7] The general principle applies that the lines of force and equipotential surfaces assume such shapes and directions that the total permeance becomes a maximum, or the reluctance a minimum.

Since the permeance $\mathcal{P}$ and the permeability μ are connected by the relation $\mathcal{P} = \frac{\mu A}{l}$, where A is the area and l the length of the path involved, the permeance can be measured from the distribution of the field and the permeability found. Analytical calculations are feasible, however, for only the simplest cases.

In three-dimensional problems a graphical method of trial and approximation must be used in order to obtain maximum permeance. Procedures have been worked out by Lord Rayleigh and Lehmann[8] for laying out such a field. The general method is to subdivide the field into small cells by means of lines of force and equipotential surfaces. The total permeance is then calculated by properly combining the cells in series and parallel. Then the assumed cells are modified somewhat and the permeance calculated again, until by successive trials the positions of the lines of force are found for which the permeance, as calculated, be comes a maximum.

Consider a single loop of wire. The electromagnetic energy possessed by such a loop at time t during the building up of flux is:

$$\left.\begin{aligned} dW &= i_t e_t dt \\ dW &= i_t \frac{d\phi_t}{dt} dt \\ dW &= i_t d\phi_t \end{aligned}\right\} \quad [4]$$

where W is in joules, i_t and ϕ_t are the instantaneous values of the current in amperes and the flux in webers at the time t and $e_t = \frac{d\phi_t}{dt}$ is the instantaneous electromotive force. The total energy supplied from the electrical source to build up the field to its final value W is

$$W = \int_0^i i_t d\phi_t \quad [5]$$

* Permeance (symbol $\mathcal{P}$) is the reciprocal of reluctance. In the simple magnetic circuit of a torus ring uniformly wound with wire if $\mathcal{F}$ = magneto motive force, ϕ = flux and $\mathcal{R}$ = reluctance, $\mathcal{F} = \mathcal{R}\phi$; $\phi = \mathcal{P}\mathcal{F}$; $\mathcal{R}$ is analogous to resistance, $\mathcal{P}$ is analogous to conductance in an electrical circuit and is expressed in henrys.

In a medium of constant permeability, $\phi_t = \mathcal{P} i_t$ where $\mathcal{P}$ is the permeance of the magnetic circuit in henrys. Any one of the three following expressions may be obtained for the electromagnetic energy stored in the loop:

$$W = \tfrac{1}{2} i\phi \qquad [6]$$
$$W = \tfrac{1}{2} i^2 \mathcal{P} \qquad [7]$$
$$W = \tfrac{1}{2} \phi^2/\mathcal{P} \qquad [8]$$

Equation 6 indicates that the magnetic energy stored in a loop is equal to one-half the product of the flux and the current. Equation 7 shows that the stored energy is proportional to the square of the current and the permeance of the magnetic circuit.

Taking the more general case of a coil of n turns, we have partial as well as complete linkages. Partial linkages mean the flux that links with part of the turns. This may be of a magnitude comparable with that of the flux that links with all the turns of the coil. Considering first the complete linkages, or the energy due to the flux that links with all the turns of the coil, we find that, by repeating the reasoning above for a single loop:

$$W_c = \tfrac{1}{2} n^2 i^2 \mathcal{P}_c \qquad [9]$$

Where subscript c = complete linkages.

The energy of the partial linkages is calculated in a similar manner and may be shown to be:[9]

$$W_p = \tfrac{1}{2} i^2 \Sigma n^2{}_p \Delta\mathcal{P}_p \qquad [10]$$

In which subscript p = partial linkage. The total energy of the coil is:

$$W = \tfrac{1}{2} i^2 (n^2 \mathcal{P}_c + \Sigma n^2{}_p \Delta\mathcal{P}_p) \qquad [11]$$

Assuming that there is no mutual inductance, by definition,

$$W = \tfrac{1}{2} L i^2$$

where L is the inductance in henrys, or

$$\begin{aligned} L &= 2W/i^2 \\ &= n^2\mathcal{P}_c + \Sigma n^2{}_p \Delta\mathcal{P}_p \qquad [12] \end{aligned}$$

replacing the summation by an integral,

$$L = n^2 \mathcal{P}_c + \int_0^n n^2{}_p d\mathcal{P}_p \qquad [13]$$

If we replace the actual coil by a fictitious coil of equal inductance and the same number of turns, but without partial linkages, we may write:

$$\begin{aligned} L &= n^2 \mathcal{P} \qquad [14] \\ &= n^2 \frac{\mu A}{l} \qquad [15] \end{aligned}$$

This theory assumes that the permeability is constant. In the case under consideration, however, approximately one-half of the field is in air and the other half in a medium of permeability μ. It is therefore necessary to calculate separately the permeance for the part of the field that is in air, and that for the part in the medium, to arrive at the correct theoretical value for the inductance L.

Permeability may be changed to susceptibility by the relation:

$$\mu = 1 + 4\pi k$$

where k is the volume susceptibility in c.g.s. units.

Experimental Work

The bridge was set up and connected to a variable-frequency oscillator in such a manner that stray induction effects between them were a minimum.

Experiments were made to determine the influence of change in frequency and of capacity and electrical conductivity of samples. The effect of different branch impedances was also investigated and the value that gave the most sensitive response to the bridge was found to be around 5000 ohms, which was the internal impedance of the oscillator output.

Frequency was shown to be immaterial to at least 2000 cycles by running tests up to that frequency with a small piece of iron in the coil. Brown[10] has shown that, in properly laminated iron, the permeability may remain constant, at the value

of that for stationary fields, at various frequencies up to one million cycles. Since the frequency was not critical, 500 cycles was chosen, as it gave a good note in the headphones used with the bridge.

To investigate the effects of any capacity in the sample, measurements of the inductances of the coil when in air and when suspended over the surface of a body of distilled water were made. No appreciable change in inductance was observed.

In a similar test with a saturated solution of salt water of high electrical conductivity, the change in inductance was so small as to be within the working error of the instrument. Since the values of the dielectric constant and the electrical conductivity of these two samples were well above any that ordinarily would be encountered in the field, these factors may be safely ignored. This was in accordance with experiments carried out by Barret.[11]

Tests were made on ferric chloride solutions and on blocks of modeling clay and sand containing evenly distributed amounts of iron filings. The susceptibilities of these samples were known, from independent determinations.

All test samples were about the same size, or with a thickness of 18 cm. The field strength at the far face of a specimen was found to be 2 per cent of that at the center of the coil. As this small error was constant, it was neglected. (See Fig. 5.)

For the ferric chloride solutions, Koenigsberger[12] gives the relation between the percentage of $FeCl_3$ and the volume susceptibility of the solution as:

$$k \times 10^6 = (88.78p - 0.78) \times d \quad [16]$$

where p is the percentage of $FeCl_3$ and d is the density of the solution.

The Smithsonian Physical Tables (Ed. 8, 1933, p. 475) also gives a relation between the percentage of $FeCl_3$ (p) and the mass susceptibility as follows:

$$K = (p/100)H + (1 - p/100)H_0 \quad [17]$$

where H is the mass susceptibility of pure $FeCl_3$, given as 90×10^{-6}, and H_0 is the mass susceptibility of water, given as -0.79×10^{-6}.

To obtain the volume susceptibility, this must be multiplied by the density of the solution used, which may be found in most chemical handbooks.

Susceptibilities obtained by the above two formulas were found to agree within better than 2 per cent.

The susceptibilities of the clay and sand samples were measured by a method developed by C. A. Heiland, which follows.

Two identical solenoids, of 3.2 cm. radius and 16.6 cm. long, were placed vertically 15 cm. north and south of a vertical-intensity magnetometer of known scale value, so that a line joining their centers passed through, and at right angles to the center of the magnetic system. The solenoid windings were connected in opposition to a battery and rheostat in such a manner that when the coils were properly centered and current was sent through them there was no deflection of the magnetometer system. However, when a paramagnetic sample was inserted in one of the solenoids, a stronger field was induced in it than was present in the one on the opposite side of the magnetometer, the effect being that of placing a magnet in the second position of Gauss, which will cause the magnet system to be deflected. Then,

$$I = M/V,$$
$$M = IV,$$
$$I = kH$$
$$M = kHV$$

where M = the magnetic moment,
I = intensity of magnetization,
V = the volume of the sample,
k = magnetic susceptibility and
H = field strength in the sample.

In the second position of Gauss, the field

due to a magnet is:

$$M/r^3 = \Delta Z = \epsilon \times \Delta s$$
$$\Delta Z = kHV/r^3$$

r = the distance from the center of the magnet.

$$\epsilon \times \Delta s = kHV/r^3$$

ΔZ = change in field strength, ϵ = the scale value of the instrument, Δs = the change in scale reading,
whence,

$$k = \epsilon \Delta s r^3/HV \qquad [18]$$

and

$$I = \epsilon \Delta s r^3/V \qquad [19]$$

The fields of the solenoids were calculated from the formula

$$H' = 0.4Ni/l \qquad [20]$$

where H' is in gauss; N = total number of turns; i, the current in amperes; l, the length of the solenoid in centimeters. This formula takes no account of the demagnetizing factor. The true field, H_0, is

$$H_0 = H'DI \qquad [21]$$

where I is the intensity of magnetization and D the demagnetizing factor. From the dimensions of the coil (l/d = 5.38), the Smithsonian Physical Tables (1933, p. 470) give 0.64 as the value of D for this ratio.

As, however, the susceptibilities of the samples used were fairly low, this correction became negligible. For example, a specimen of susceptibility 2060 $\times$ 10^{-6} had an intensity of magnetization of 0.206 c.g.s. units at a maximum field strength of 100 gauss.
Then,

$$\begin{aligned} H_0 &= H' - DI \\ &= 100 - 0.64 \times 0.206 \\ &= 100 - 0.13 \\ &= 99.87 \end{aligned}$$

This is a difference of only 1.3 in 1000 at 100 gauss. (This sample had the highest susceptibility of any used.)

To determine how the calculated values of susceptibility compared to those found by the deflection magnetometer, investigations were made at various field strengths with solutions of 30 and 50 per cent ferric chloride. $FeCl_3$ was used and the calculated values were obtained from equation 17. The observed and calculated values at a field strength of 100 gauss follow. Susceptibilities are in 10^{-6} c.g.s. units.

	k		Δk
	Observed	Calculated	
30 per cent $FeCl_3$.......	15.6	16.1	0.5
50 per cent $FeCl_3$.......	29.6	28.9	−0.7

The results are shown graphically in Fig. 2.*

Fig. 3 shows a series of I-H curves obtained with this instrument. Readings were taken at every 10 gauss up to 100 gauss.

Table 1 shows the computations for curve 3 in Fig. 3, as it is typical of all the others.

TABLE 1.—*Computations for Curve 3, Figure 3*

H, Gauss	Field at Balance		I from Eq. 19	$k \times 10^6$ Eq. 18
	Gammas	Gauss		
10	32	0.00032	0.01000	1000
20	66	0.00066	0.02060	1030
30	106	0.00106	0.03310	1103
40	150	0.00150	0.04680	1170
50	193	0.00193	0.06020	1204
60	232	0.00232	0.07250	1208
70	276	0.00276	0.08610	1230
80	319	0.00319	0.09950	1243
90	362	0.00362	0.11310	1250
100	405	0.00405	0.12630	1263

There is a slight bend at the bottom of each curve, which otherwise is linear. Since the field strength of the search coil used

* In Figs. 2 and 4, ordinates are given as susceptibility $\times$ 10^6 = 0, 4, 8, 12, etc. or 0, 400, 800, respectively. This means that for a point on one of these curves the susceptibility would be, say, 4.3 $\times$ 10^{-6} or 405 $\times$ 10^{-6}, for example.

in the experiments was only of the order of 4 gauss, the susceptibilities of the samples was taken at this value when plotting the calibration curve, Fig. 4.

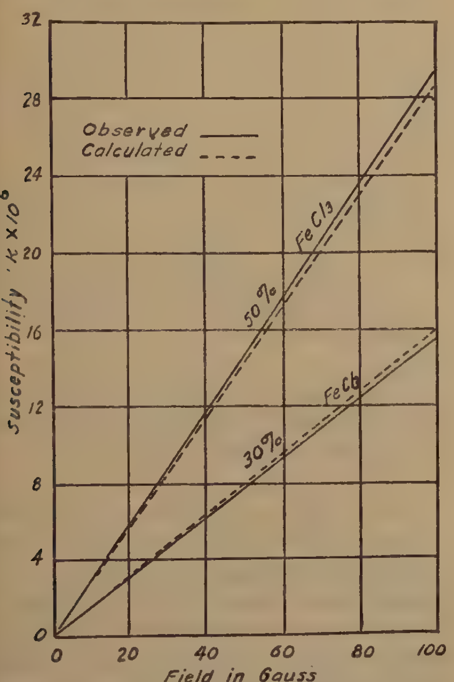

FIG. 2.—CALCULATED AND OBSERVED VALUES OF k FOR FERRIC CHLORIDE SOLUTIONS.

This will necessitate keeping the current in the bridge constant and specifying at what field the susceptibilities were measured; in this case 4 gauss.

In the tests made on specimens with the bridge, the search coil was first laid on a wooden stool, free from iron, and its inductance was determined, making sure that its inductance on the stool was the same as though it were suspended in air. The inductance L_1, for the coil in air, was found from the equation of the bridge

$$L_1 = RQC_2$$

Next, the block-shaped sample was placed on the stool and the coil laid flat on its surface. Several readings were taken with the coil reversed on the block and the block also reversed. The mean of these values was used in the calculation of L_2 in the same way that L_1 was calculated. The difference, ΔL, in the inductance of the coil, when laid

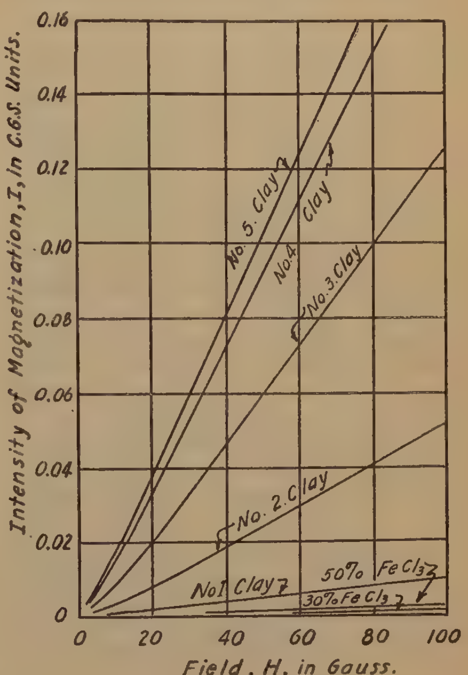

FIG. 3.—I-H CURVES.

flat on a magnetic medium and when in air is thus found. Care was exercised to see that the inductance of the coil came back to its normal value for air after readings had been taken with a sample present. The change in inductance was found for each value of known susceptibility available, and from these data the calibration curve, Fig. 4, was constructed.

Thus, to find the change in inductance caused by, say, sample No. 2, the bridge was balanced first in air. At the point of balance, the following values were obtained: $R_1 = 5000$ ohms, $Q_1 = 3559$ ohms, $C_2 = 0.01$ microfarads. From equation 3, L_1 was found to be 0.179950 henrys.

Then with the coil placed flat on the sample, Q was changed to 3609.3 ohms to again balance the bridge. The new induct-

ance L_2 was calculated in the same manner and was found to be 0.180460. The difference, ΔL, between L_1 and L_2 was then 0.000510 henrys, or 510 microhenrys.

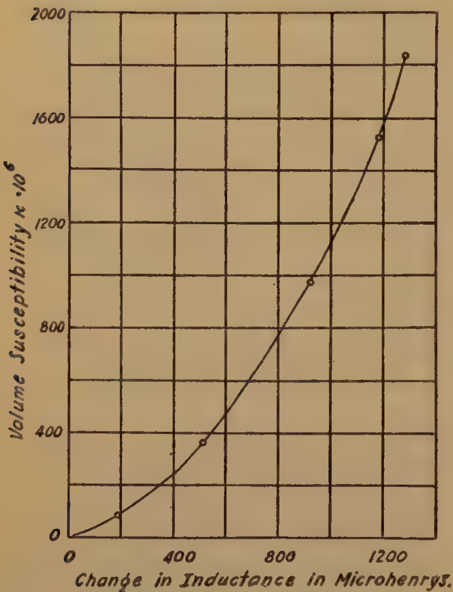

FIG. 4.—CALIBRATION CURVE REDUCED TO A FIELD OF 4 GAUSS.

In the calibration curve showing the susceptibility, k, reduced to a field of 4 gauss, is plotted against the change in inductance ΔL of the search coil from its zero value. Since the inductance is directly proportional to the resistance Q, however, the latter may, if desirable, be plotted against k and a certain amount of labor eliminated.

In field work it is, of course, necessary to have the coil flat on the rock at all times. If this is not so, a part of the magnetic field will not pass through the rock, causing a value of k smaller than the correct one to be recorded. The value of the field strength at the center of a circular coil of n turns and radius r cm. is

$$H = 2\pi ni/r \qquad [22]$$

The field along the axis of the coil drops off rapidly with an increase in distance from the coil. At a distance x from its center

$$H = 2\pi nr^2 i/(x^2 + r^2)^{3/2} \qquad [23]$$

This relation is shown graphically in

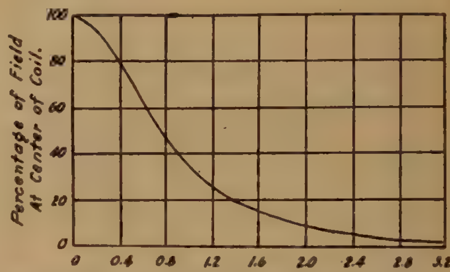

FIG. 5.—VARIATION OF FIELD STRENGTH WITH DISTANCE FROM CENTER OF CIRCULAR COIL.

Fig. 5, where the ratio of the distance x and the radius r is plotted against the percentage of H at the center of the coil. At a distance from the coil equal to three times its radius, the magnetic field has dropped to about 3 per cent of its maximum value. Thus, the larger the coil, the greater is the volume of rock under test. This may be important in connection with, for example, a not too compact rock containing magnetite, where weathering may have altered the magnetite to hematite or limonite for a short distance from the surface. It is best, therefore, to use as large a coil as is practicable.

CONCLUSIONS

It is believed that the best values of susceptibilities of rocks and formations are those determined in the field by readings taken on the undisturbed rock. A method for doing this by the use of an alternating current bridge has been devised and shown to be practicable. Integral parts of the instrument may, after experimentation has determined their best values, be replaced by standards of those values having small dimensions, so that the complete instrument will be small, compact, and readily portable.

References

1. C. A. Heiland: *Trans.* A.I.M.E. (1932) **97**, 234–236.
2. E. Wilson: Measurement of Magnetic Susceptibilities of Low Order. *Proc.* Roy. Soc. (1879) 29-A, 429.
3. B. Hague: Alternating Current Bridge Methods. London, 1932. Sir Isaac Pitman and Sons Ltd.
4. D. Owen: A Bridge for the Measurement of Self-induction in Terms of Capacity and Resistance. *Proc.* Phys. Soc. (1915) **27**, 35–39. (See also ref. 3.)
5. J. A. Fleming: The Principles of Electric Wave Telegraphy and Telephony. New York, 1916. Longmans Green and Co.
6. E. B. Rosa: On the Geometrical Mean Distances of Rectangular Areas and the Calculation of Self-inductance. *Bull.* Nat. Bur. Stds., **3** (1), 1–41.
7. V. Karapetoff: The Magnetic Circuit, Art. 41. New York, 1911. McGraw-Hill Book Co.
8. T. Lehmann: Graphische methode zur Bestimmung des Kraftlinienverlaufes in der Luft. *Elektrotech. Ztsch.* (1909) **30**, 995.
9. V. Karapetoff: *Ibid.*, article 57.
10. R. Brown: The Characteristics of Iron in High-frequency Magnetic Fields. *Jnl.* Franklin Inst. (1917) **183**, 41–59.
11. W. M. Barret: A Semi-portable Alternating Current Susceptibility Meter. *Physics* (Sept. 1932) **3** (3), 149–154.
12. J. G. Koenigsberger: Method for Measuring the Susceptibility of Rocks. *Terr. Mag. and Atmos. Elec.* (Sept. 1929) **34** (3), 209–214.

DISCUSSION

(J. J. Jakosky presiding)

E. A. Eckhardt.*—Have you encountered in any of your measurements the phenomenon of the intensity magnetization of your sedimentary rock specimen depending very much on the time in which you leave it in the weak field? We have been having considerable trouble because of a phenomenon of that kind, which seems to be rather common.

C. A. Heiland.†—Do you mean this effect results from the use of larger fields?

E. A. Eckhardt.—No, I mean simply this: You magnetize the specimen and put it into the field, and what you get depends very much on how long you leave it in that field.

C. A. Heiland.—That is very true. We have observed that a number of times when static susceptibilitv determinations were used. The effect did not appear noticeable with the (a.c.) induction method, particularly in small fields and with low susceptibilities.

D. C. Skeels.*—How large a field did you use when you determined the susceptibility of the material originally?

C. A. Heiland.—The fields were varied between 10 and 100 gauss in the solenoid measurements. The field of the induction coil was approximately 4 gauss.

D. C. Skeels.—Would there be any erorr introduced in using that same susceptibility to calibrate the coil; that is, when you calibrate the coil it is in the smaller field, is it not?

C. A. Heiland.—I do not think so, because the susceptibilities were taken from the I-H curves obtained by the solenoid method at the 4-gauss point and these values were then used to calibrate the induction coil. You refer, I believe, to the variation of susceptibility with field strength, which is much less pronounced in sedimentary rocks than in igneous rocks. I do not know whether this has anything to do with molecular structure; in any event, a relation between grain size and susceptibility seems indicated.

D. C. Skeels.—That is a very important point. Much suspicion has been cast on susceptibility measurements made in high fields, because we know that with iron, and some other metals, the susceptibility varies tremendously with the strength of the measuring field.

C. A. Heiland.—The idea back of the methods referred to in the paper is to get the susceptibility for various field strengths; in other words, a complete hysteresis curve is obtained, with induced magnetism, coercive force, and susceptibility. I think those are the ideal methods.

A. C. Lane.†—Some work has been done on antiquarian Roman bricks, and similar materials. Have you tried any of those?

C. A. Heiland.—No, we have not. The purpose of this paper is primarily to describe a new technique.

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* Gulf Research and Development Corporation, Pittsburgh, Pa.

† Heiland Research Corporation, Denver, Colo., and Professor of Geophysics, Colorado School of Mines, Golden, Colorado. Dr. Heiland presented Mr. Paterson's paper.

* Research Geophysicist, Standard Oil Company of New Jersey, New York, N. Y.

† Geologist, Cambridge, Massachusetts.

Natural Potentials in Sedimentary Rocks

By Parke A. Dickey,* Member A.I.M.E.

(New York Meeting, February 1943)

Abstract

Potential differences between strata of shale and sandstone have been recognized for about 15 years, and they form the basis of the electrical logging of oil wells. Hitherto these potentials have been ascribed solely to electrochemical reactions caused by the disturbing effects of the water in the drill hole through which they are generally measured. Observations by the author in wells empty of water and in a mine shaft suggest that potential differences between sandstones and shales are natural and specific properties of the rocks, although they are modified in measurement by the disturbing effects of the water in the drill hole. The cause of these potentials probably is to be sought in the relative polar adsorptive capacities of quartz and clay particles.

Introduction

The existence of potential differences in the surface of the earth has been known for some time, and their measurement has facilitated the discovery of geological discontinuities such as ore bodies. The technique of measurement has been well established.[1-3]

In measurements in oil wells, it has been found that the potential of shales with respect to some arbitrary reference is very nearly constant in any one well, at least below the zone to which meteoric water has gained access. Sandstones and some other types of sedimentary rocks have a difference of potential with respect to shale that is negative and may attain a value of 200 millivolts or more. The difference of potential, as usually measured commercially with water in the hole, is distributed over about one foot vertically at the top and bottom contacts of the sandstones. The sharpness of the curve at the formation contacts can be improved by using a short electrode that is close to the wall of the hole.

These potentials generally have been ascribed to the disturbing effects of the water in the drill hole. Potentials have been found, however, in wells in which no water was present. In the course of experiments in electrical logging in Pennsylvania, carried out by the Pennsylvania Geological Survey, observations were made of several phenomena that hitherto have not been described, to the author's knowledge, in the published literature.

The potential differences across the contacts of sandstone and shale are called in this paper "natural potentials," as distinguished from the potentials caused by electroendosmosis (electrofiltration) and concentration differences, which will be discussed subsequently.

Potentials in Cored Well

In the spring of 1942, the author measured the potentials in an exploratory well (Day 13, near Grand Valley, Pa.) which had been cored with diamond tools. The potentials were first measured with fresh water in the hole. A null balance potentiometer was used in this and all the other measurements described in this paper. One nonpolarizing porous pot electrode, containing copper sulphate solution and

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* Forest Oil Corporation, Bradford, Pa.

[1] References are at the end of the paper.

crystals surrounding a pure copper electrode, was lowered into the well. Measurements were made every 0.5 ft. with reference to a similar electrode on the surface near the well. On another occasion a log was made with a continuously recording instrument, but it does not show any more detail than the log made from readings at 0.5-ft. intervals.

The hole was then bailed dry, and allowed to stand for several days, after which the potentials were measured in the empty hole with an improvised wall contactor (Fig. 1). This was a contrivance consisting of three legs (like umbrella ribs), which were lowered collapsed, and on reaching the bottom were tripped, so that they came out rubbing against the walls of the hole. It was made of iron with brazed joints. The legs were sheathed in rubber, and actual contact with the wall was made with a lead ball attached to one of the legs. The results were not considered satisfactory, since the metal got wet and the contact potentials were high. They were, however, reasonably constant. Readings were taken every 0.1 ft. but occasionally the lead ball would lose contact with the wall of the hole and a reading would be lost.

A comparison of the curves obtained with the hole empty and full of water is shown in Fig. 2. The empty-hole log shows a great deal more detail than the log with the hole full of water. This is to be expected, since the 6-in. column of water would have a short-circuiting and smoothing effect on the potential differences, regardless of their origin. The difference of potential between the maxima and the minima is about 25 mv. in the empty hole and 60 mv. with the hole full of water. This difference is believed to be due to the absence of the solution concentration potentials in the empty hole.

The section logged consisted of thinly interstratified hard quartzitic sandstones and shales. Some of the thicker sandstone beds contained oil, although not in commercial quantities. The curve in the empty hole was plotted on coordinate paper to 1:1 scale, and laid out along the diamond

FIG. 1.—WALL CONTACTOR.

core (Fig. 3). Although observations frequently were missed, most of the sandstones (white or gray in the picture of the core) are matched by high negative values, while the shales (black) are rather constant. It seems likely that beds as thin as 0.1 ft. may be detected in empty holes.

MEASUREMENTS AT FRANKLIN SHAFT

During the summer of 1942 a shaft was sunk about 425 ft. to the Venango First oil sand at Franklin, Pa. Detailed measurements were made of three short vertical sections near the top of the oil sand, about 2 ft. apart horizontally (Fig. 4). One nonpolarizing porous pot electrode was placed at the surface, and the other was touched to the rock, the potential differ-

ence being measured with a potentiometer (Fig. 5). Referred to the surface electrode, the shales had a potential of about minus 60 mv., and the sandstones and conglomerates about minus 90 mv. The full drop of potential extended over less than 3 in., most of the gradient being concentrated within the sandstone. In the farthest right section of Fig. 4 there was a stray bed of conglomerate, ½ in. thick, separated from the main conglomerate bed by ½ in. of shale. Even this thin bed showed a negative potential of 15 mv. A curious drop of potential at the contact of conglomerate and underlying sandstone was noted, although no shale was observed at this point.

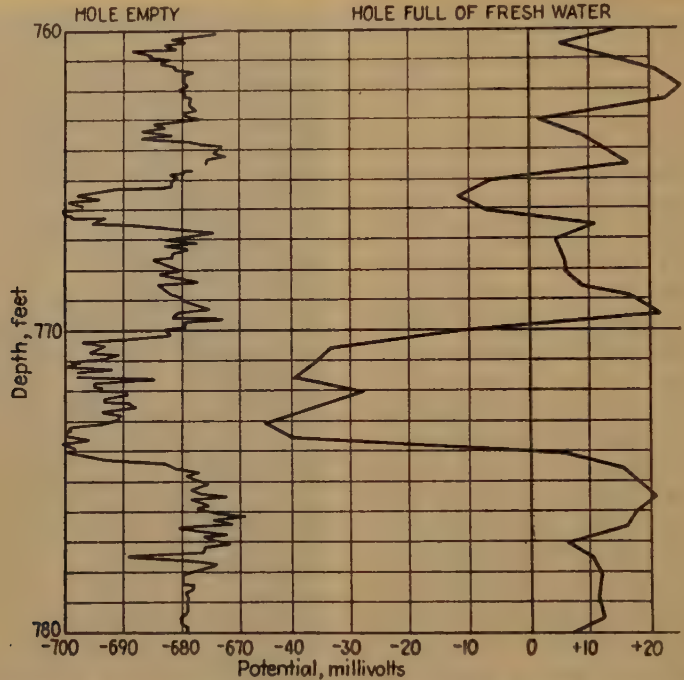


Fig. 2.—Comparison of potential curves obtained in hole full of fresh water and in empty hole.

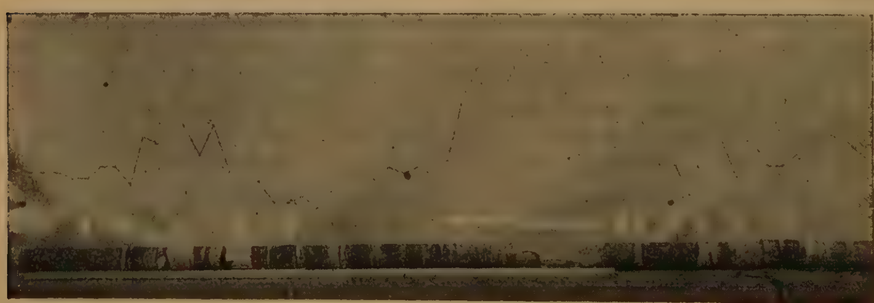


Fig. 3.—Comparison of potential log and diamond core.

A bed of sandstone above the oil sand, plotted in its proper position in the upper left corner of Fig. 4, contained darker

streaks of shaly sandstone running irregularly through it. The potential in the shaly beds was 5 to 10 mv. lower than in the pure sandstone.

Some weeks later another shale and conglomerate bed was encountered about 30 ft. below the top of the sand. The potentials in this series were measured directly below the previous measurements. It happened that this point was near the outlet of the air pipe, and air had been blown over the face of the rock for about a week prior to the measurement. Small amounts of water had condensed on it and the shale had begun to slack and crumble. The potential differences between the sand and shale were less than 2 mv. At a more recently exposed point in the same bed, about 20 ft. away horizontally, the potentials were quite sharp and had a value of about 20 mv. Fig. 6 is a photograph of this place, with the potentials plotted on the picture.

Potential measurements were also taken at the base of the sand, but no difference in potential between the sand and the underlying shale was found. The lower part of the sand contained a good deal of salt water, which, at the time the measurements were made, had been slowly seeping down over the face at the contact. It is considered probable that this salt water either short-circuited the potentials electrically or removed their cause chemically.

After making the measurements in the mine, the movable electrode was touched to numerous chunks of sandstone and shale as they lay on the dump, some of which had been exposed to the atmosphere for several weeks. Each chunk had a definite potential. As a rule the sandstones were more negative, but occasionally one was found with a positive potential with reference to an adjoining shale chunk. Three samples were measured relatively to each other, both sandstone and conglomerate being about 20 mv. positive with respect to the shale. After soaking in tap water separately for about a week, the water being changed occasionally, the potentials were unchanged.

Potential differences between sand and shale have also been noted by the author in fresh drill cores. There seems little doubt that the potential difference is a specific property of the rock and its contained electrolyte, although it may easily be changed by contact with different electrolytes.

Contacts of Sandstones and Shales

From the foregoing observations the author is inclined to believe that potential discontinuities exist at the contacts of sandstones and shales, in subsurface strata that contain strong connate water. It is probable that in near-surface formations circulating meteoric waters have destroyed the uniform potential layers. If these potential discontinuities do exist permanently, a new attack on the theory of surface resistivity measurements may be required. The presence of such permanent potential layers had been suspected previous to the work described in this paper. Lee[4] in 1939 published certain observations that could be explained only on the basis of potential layers in the earth. Potential measurements in oil wells empty of water have been made for several years, although none of the results have been published, to the author's knowledge.

It is believed that potential observations in oil wells empty of water may have important practical significance in districts where great accuracy in the location of the tops and bottoms of formation is required. No satisfactory electrode has been constructed as yet. The author believes that it will have to be of the nonpolarizing type, so constructed that a positive contact of small area will be made against the wall of the hole at all times.

It is not the intention to formulate here a hypothesis to account for the natural potential differences between sandstones and shales. It seems probable, however,

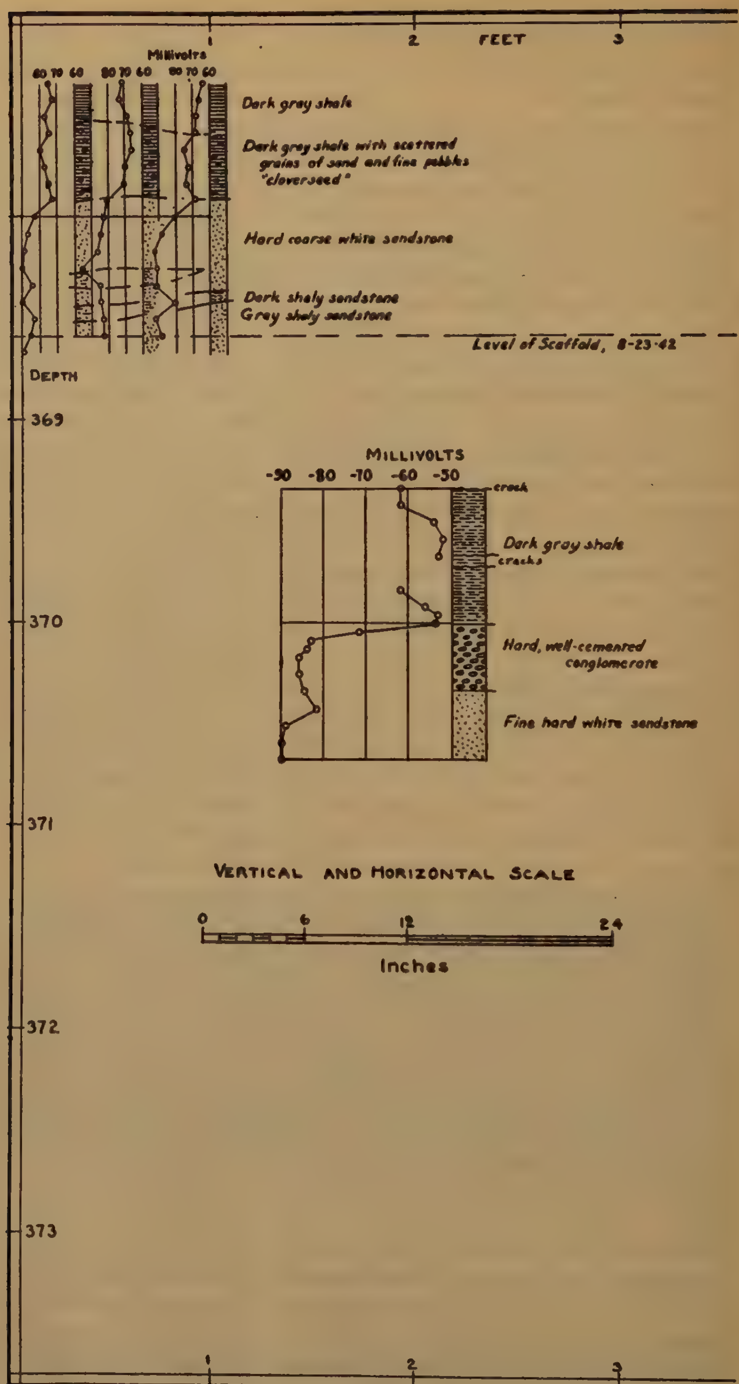
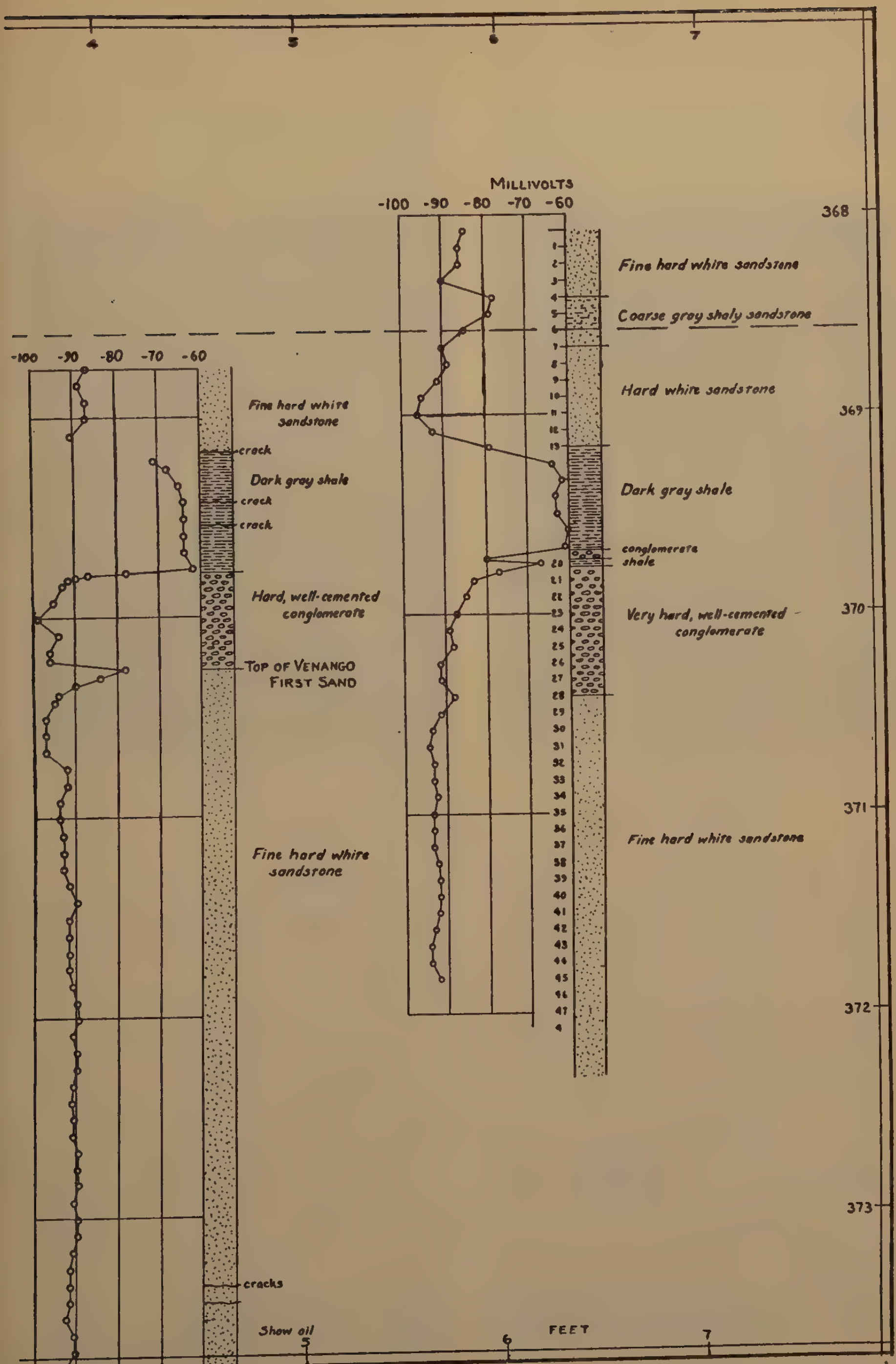


FIG. 4.—POTENTIAL LOGS



IN FRANKLIN MINE.

that the cause is related to selective adsorption by the colloidal clay particles of the ions of the connate water contained in the sedimentary rocks.

It is well known that most solids acquire a potential difference when immersed in a solution of an electrolyte. Certain substances, among them kaolin, which is chemically similar to shale, strongly adsorb the positive ion in preference to the negative ion of the electrolyte. It seems probable, therefore, that an electrolyte contained in the pores of a shale that is a strong polar adsorbent and has an enormous internal surface, might have a considerably different ionic composition from that contained in a sandstone. The phenomena involved are complex and probably would not be easy to study experimentally.

FIG. 5.—MEASURING POTENTIALS IN MINE SHAFT.

The effects of electroendosmosis and solution-concentration potentials, to which the existence of earth potentials in oil wells is generally ascribed, unquestionably also exist, and they modify the natural potentials.

SOLUTION-CONCENTRATION OR "CONCENTRATION-CELL" POTENTIALS

When two solutions of the same salt, but of different concentrations, are placed in contact, a potential difference is formed at the interface. Equations have been derived to determine the electromotive force of the cell, which depends on the relative velocities of the ions and the concentration of the solutions. The phenomenon is essentially transitory, since the solutions tend to diffuse; in fact, it is the diffusion that gives rise to the potential. This makes the potential difficult to measure even in the laboratory. It appears to be impossible to predict the effect of this phenomenon in an oil well. It could be measured only by placing one electrode in the well and another back in the rock completely isolated electrically from the well, which manifestly is impossible. Therefore it is impossible to calculate the effect of the solution concentration potential on the total potential measured.

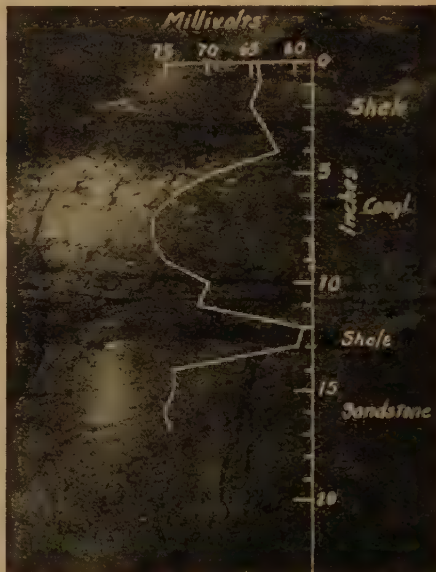


FIG. 6.—SHALE, CONGLOMERATE AND SANDSTONE IN FRANKLIN SHAFT, SHOWING OBSERVED ELECTRICAL POTENTIALS.

This source of potential is very important in measurements of potentials in wells containing water. The magnitude of the potential difference between sandstone and shale in wells containing fresh water is much greater than that in wells containing salt water. Some of this diminution in magnitude may be due to a short-circuiting effect as the conductivity of the well water is increased. The potential differences are greater in wells containing fresh water than in empty holes. They did not exceed 30 mv. in the author's observations, while potentials of over 100 mv. are common in wells containing fresh water.

Well Day 13 was filled with fresh water, then the potentials were measured every day for four days. They diminished notably both in amplitude and in the sharpness of their variations at lithologic changes during that period (Fig. 7). This deterioration may be due to: (1) removal by osmosis of the salts in the connate water, thereby decreasing the concentration cell potential, or (2) the removal of the cause of the natural potentials. Although this deterioration of the potentials as water was allowed to stand undisturbed on the formations has been observed frequently in Pennsylvania, it does not occur when the well is drilled with rotary tools and mud is continuously circulated past the rock. This mud forms a "filter cake," which effectively prevents the entrance of fresh water into the sandstones. Although in no case was a potential difference found in wells in which water had stood undisturbed for several months, an excellent log was obtained after cleaning out the Atlas well, near Grand Valley, Pa., that had been standing full of water for more than 70 years.[6] Apparently the motion of the water or the tools enables the sources of potential to exist. In spite of numerous attempts, the author has never been able to obtain a log of a well full of salt water from an upper horizon.

Electroendosmosis or Electrofiltration

It was first observed by Reuss in 1807 that a liquid will move across a porous

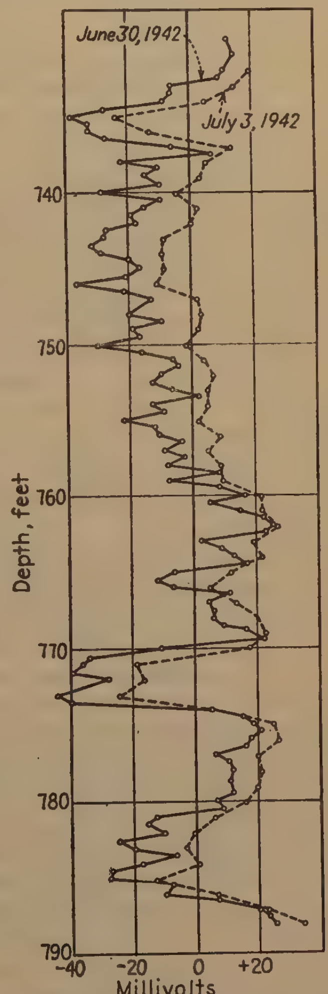


Fig. 7.—Potential log of well Day 13, showing deterioration of amplitude and detail of potentials after four days with fresh water standing in hole.

diaphragm under the influence of a potential difference. This phenomenon has been extensively studied since that time,[7] and has been called endosmosis or electro-

endosmosis. It has been found that under most circumstances when a solid is placed in contact with a liquid an electrically charged double layer is formed between the surface of the solid and the liquid. The introduction of an electrode on either side of a porous diaphragm that is negatively charged by this effect will induce a flow of liquid toward the cathode. Conversely, if the liquid is forced to move through the diaphragm by a pressure differential, an electromotive force will be produced.

Equations to relate the velocity of movement to the constants of the system and the potential gradient have been derived, but it is very doubtful whether such equations can be applied to the conditions in an oil well in order to determine how much of the total potential is due to electroendosmosis. We are dealing not with a diaphragm, but with a massive porous stratum. It is impossible to place one electrode on one side and the other on the other side of this stratum.

In fresh-water strata, potential effects possibly due to electroendosmosis have been noted. In the Atlas well, mentioned above,[6] a near-surface sandstone that was known to be discharging water into the well showed a potential that was positive with respect to the shales. In an experiment performed in 1937 near Bolivar, N. Y.,[8] it was found that in a sand that had been thoroughly flushed with fresh water a higher pressure on the water in the well caused an increased negative potential opposite the permeable sand stratum that was taking the water. The well had had fresh water injected into it for several months. Potential measurements were made at various pressures of water on the sand face, and the ratio of the pressure and the product of the sand thickness and potential difference in millivolts was linear.

In the course of numerous experiments on normal wells containing oil-bearing and salt-water-bearing sands, increasing the pressure of the water in the hole did not increase the potential differences. In Pennsylvania, a relation between the potentials of the sandstones and their permeability as determined by laboratory tests and the injection of gas has been noted,[6] but this relation is believed to be due to the presence of more clay in the less permeable sandstones. Similarly, the differences in potential observed in the Franklin shaft are believed to be caused entirely by the amount of shale in the rocks and not by their relative permeabilities. The permeability of a rock is determined by the average pore diameter and pattern, which is affected by both the size of the quartz grains and the amount of shaly material. The experiments described above suggest that the potential differences, as ordinarily measured, are determined mainly by the amount of shaly material. Therefore they tend to vary with the permeability, but are not a function of the actual permeability in millidarcys. It is believed that two sands of different grain size, and therefore permeability, will show the same potential if they are equally free from shaly material. Conversely, two sands of the same permeability, but of different shale content, should have different potentials.

Acknowledgments

The author wishes to express his appreciation to all those who assisted in the experiments described. In particular, he is indebted to the Venango Development Corporation for permission to make the measurements in the mine shaft, and to the J. P. Eaton Corporation for the opportunity to experiment with well Day 13.

He acknowledges much help and advice from F. W. Lee, of the U. S. Bureau of Mines, and H. Guyod, of the Halliburton Oil Well Cementing Co.

All the measurements were made with the assistance of L. S. Clough, Jr., to whom the author is greatly indebted. Robert B. Bossler, of the Brundred Oil Corporation, made the contactor for dry-hole logging.

The writer is grateful to George H. Ashley, State Geologist, under whose direction the work was done, and to William S. Livengood, Jr., Secretary of Internal Affairs, for permission to publish this paper.

References

1. J. J. Jakosky: Exploration Geophysics. 1940.
2. C. A. Heiland: Geophysical Exploration. 1940.
3. C. and M. Schlumberger and E. G. Leonardon: Electrical Coring. *Trans.* A.I.M.E. (1934) **110**, 237.
4. F. W. Lee: The Possibility of Electrical Stratification in the Earth as Disclosed by Surface Measurements of Currents and Potentials. *Trans.* Amer. Geophysical Union (1939) pt. III, 383–389.
5. H. J. Creighton: Principles of Electrochemistry. 1935.
6. P. A. Dickey: Electrical Well Logging in the Eastern Fields. Penn. Topographic and Geol. Survey, Prog. Report 129 (1942).
7. T. R. Briggs: Electrical Endosmose. *Jnl. Phys. Chem.* (1917) **21**, 198–237.
8. R. C. Earlougher: Private report to Sloan and Zook Co., Bradford, Pa., 1937.

DISCUSSION

A. C. Lane.*—This paper suggests interesting observations, which may well be of practical importance. I entirely agree with the author's conclusions that natural "potential disconformities exist at the contacts of sandstones and shales in subsurface strata that contain strong connate water." Indeed that is shown by the way sandstone may be cemented either by pyritic deposits or carbonated just below its contact with shales. It is also true that the interstitial water itself differs in composition. Even "dry" shale and sandstone are not free from interstitial water, and the connate water may be affected bentonitic alteration of volcanic ash or organic changes such as lead to the reduction of sulphates, but is not so likely to be affected by circulation.

He does not happen to mention limestone, but limestone and shale also may react quite differently to such an indicator as, say, methyl orange.

F. W. Lee.†—The experimental measurements by Dr. Dickey, made directly on members of formations in place, establish beyond all doubt the existence of what are generally termed "electrical double layers" between formations. Helmholtz and Maxwell first explained that a very abrupt change of potential for a system without a charged field around it might well be due to such a double layer. In the limit such separations of charged surfaces are of molecular dimensions. This is found, for example, between the zinc electrode and the electrolyte in a battery. Here the phenomenon extends over a very small space interval when compared with the thickness of the geologic beds in question. It may be expected then that such demarcations in geologic beds would extend over a small space interval, although of a much greater thickness than molecular dimensions.

Fundamentally, such double layers generally signify a condition of electrical equilibrium, whether current flows between them or not. Dr. Dickey has shown that the electrical intensities encountered are of the order of 100 mv. per centimeter, generally much greater than the electrical intensities caused by the applications of electrical currents to the ground. This materially modifies a large part of the theoretical computations of the ground conductivities based on layered beds of different resistivities, and reduces such analyses to the very restricted geological cases in which no electrical polarization is present at all, or where it is only very slight.

It also modifies, to a great extent, some of the theories related to the explanations of electrical potentials associated with the sands encountered in electrical well logging. It has been contended that the driller's mud gave rise to infiltration potentials, and whenever the penetration of the mud into the sand was deep, the electrical potentials were correspondingly high. As a matter of fact, potentials have been found to be present whether the well is filled with mud, water, gas or air.

Dr. Dickey has also shown experimentally that such potentials diminish very rapidly after exposure to air. This would indicate as the best procedure the making of the potential survey as soon as the well is drilled; using a non-short-circuiting driller's mud. The measurements would require material modification whenever the well is rapidly filling with connate salt waters, which would tend to short-circuit such beds.

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† Chief, Division Geophysical Exploration, Bureau of Mines, Baltimore, Maryland.

The fact that the apparent electrical ground resistivity is only a convenient index number for electrical ground characteristics has long been recognized by the geophysical profession. The condition mentioned above definitely affects the depth of penetrations of electrical currents into the ground. Based upon the Newtonian field theory, in a uniform medium the depth of penetration would be infinite; actually it is very much restricted by such electrical double layers. The classification and characteristics of such double layers have proved very convenient for mapping stratigraphy and geologic structure. It has been possible to work through geological unconformities of the worst type, such as lava flows, and map the bed contacts below them.

Double layers near the ground surface materially modify the propagation of wireless waves, producing high damping if the resistivity of the beds above them is high, and distortion when the electrical intensities are sufficiently great to penetrate the double layers. Under the condition electrical double layers tend to act, in an electrical system, more or less in the same manner as acoustic damping used on wall surfaces.

This ground condition is of direct concern to geologist and mineralogist in relation to the paragenesis of ore deposits. The question concerning the manner in which ore is segregated has always intrigued the mineralogist, particularly when he finds the minerals disseminated through large volumes of "host" rock. The presence of natural telluric currents flowing through large areas would slowly move the metals molecule by molecule from this "host" rock to the boundary of such a double layer where deposition would take place. Further segregation is more easily understood by the concept of general mass transportation arising from clastic and hydrogenetic actions in shear zones, faults, etc.

Present day thought recognizes the value and application of the electrical theory of matter although the implication may seem at first sight only remotely connected to geological theory. But here is what the geologist calls a "fenster," or window, through which broader vision and clearer planning may be possible as a result of such research activities.

The Use of Electrode Spacing in Well Logging

By Richard H. Zinszer,* Junior Member A.I.M.E

(Los Angeles Meeting, October 1942)

Abstract

Application of electric logs has been used in correlation of subsurface structure to determine the size and shape of the oil reservoir. Such a knowledge is hardly complete until saturation and productivity are determined for the various horizons. It is difficult to use electric logs successfully for this purpose because of the many factors that influence the curves. In this work an effort was made to establish an empirical correlation between formation resistivity for a series of electric-log curves and water saturation and oil productivity of sand. Electric logs were obtained by recording with 10 different electrode spacings through the same interval of a well. In the analysis of these curves all factors except two, a dependent and independent variable, were held constant. The interval studied had been cored and a large number of samples were analyzed in the core laboratory in order to compare the values of permeability and saturation with the measured values of formation resistivity.

Results of this analysis indicate: (1) the depth to which mud filtrate enters a sand body, (2) a correlation between permeability and sand resistivity for shallow penetration depths, and (3) that the water saturation for an oil sand can be determined from the measured sand resistivity after making suitable corrections for sand thickness. The procedure in the last method depends on a correction for thickness factor and a theoretical curve. The accuracy of the theoretical curve is now being tested in the laboratory

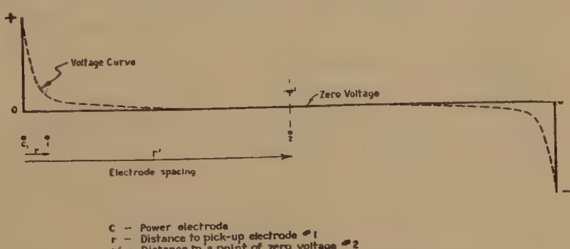

Fig. 1.—Typical voltage curve.

Introduction

In an effort to place the analysis of electric logs on a quantitative basis, there is need for a better understanding of the many factors that influence an electric-log curve. These factors may be large differences in sand thickness, permeability of the sand, salinity of the interstitial water, mud resistivity, formation temperature, and other sources. A number of examples were presented by Archie,[1] which treat the effect of sand thickness on measured resistivity. He compared the true resistivity of a sand with the observed resistivity for sands 8 ft., 16 ft., and 24 ft. thick, and found the observed resistivity of the 8-ft. sand to be approximately

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[1] References are at the end of the paper.

50 per cent of the true resistivity. He also developed an equation involving the formation factor that is used to calculate water saturation in thick sand bodies.

analyzed. Laboratory tests are still in progress to determine the accuracy of one curve presented in the report, which relates the resistivity of a sand to the percentage of water saturation at several salinities.

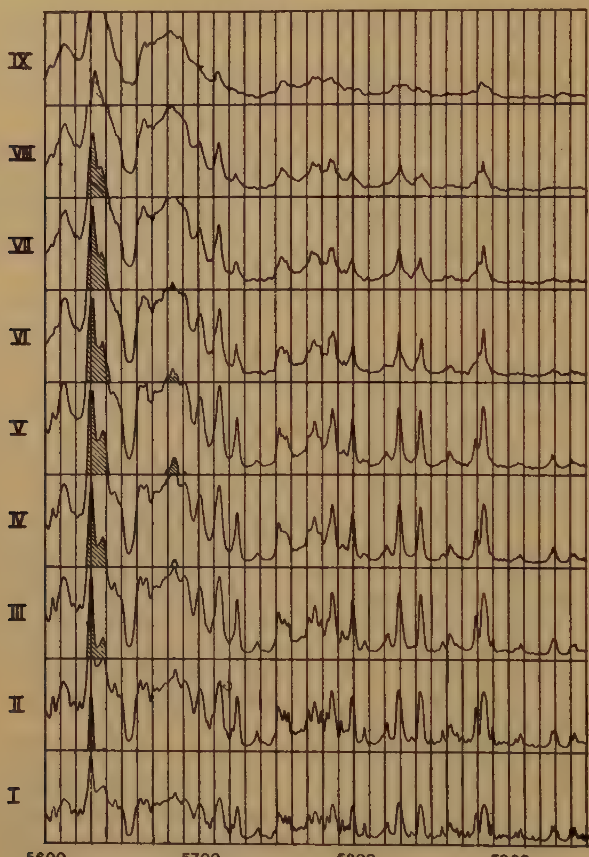

FIG. 2.—RESISTIVITY CURVES FOR SEVERAL ELECTRODE SPACINGS.

In the present work the thicknesses of the majority of the sands ranged from 1 to 10 ft., with only one 30-ft. sand. All of the data were obtained from one well in the Rosecrans oil field, California. This variation in sand thickness is typical of the producing horizons in California and no doubt accounts for the slow progress in the quantitative analysis of electric logs. The present study appears to lend itself to a statistical correlation because of the large number of thin sands cored and

On initiating the experimental runs, electrode spacings were increased from 5 in. to 89 in., through a large number of increments, in an effort to follow the change in measured resistivity to points beyond the distance to which mud filtrate would enter a sand body. In addition, the many thin sand bodies encountered during coring presented an opportunity to relate sand thickness to the measured resistivity.

Experimental Data

The well chosen for the experiment was cored continuously from 5550 to 6447 ft. At intervals in this operation it became necessary to stop the coring in order to ream the hole. The time from the start of coring at 5550 ft. to the running of the electric log amounted to 12 days, during which period the upper portion of the cored hole was subjected to 11 round trips of the bit, as compared with one round trip for the lower part of the hole. Circulation of mud was continued 4 hr. after the last core was taken, in order to ensure a uniform conditioning of the mud.

Table 1 lists the electrode spacings used in this electric-log survey for a single potential and single pickup device.

Fig. 1 illustrates the positions of the electrodes with respect to a simple voltage curve that might exist in a homogeneous formation. The present use of the term "depth of penetration" referred to in Table 1 is a relative expression for comparing the effect of the electrode spacings.[2] This expression determines an approximate distance in a homogeneous formation to a point at one-half the voltage between that of r (distance to the pickup electrode No. 1) and that at r' (distance to a point of zero voltage No. 2). This can be expressed by:

$$D.P. = \frac{2rr'}{r + r'}$$

This equation gives a practical concept to the effect of electrode spacing, which can be readily used for correlating.

Table 2 lists pertinent data relating to the test. It should be noted that the mud temperature of 160°F. differs from the formation temperature of 188°F. The

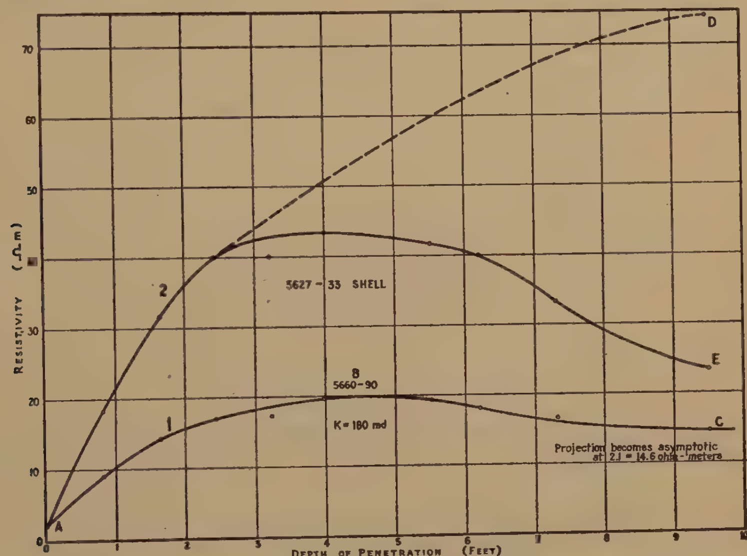

Fig. 3.—Comparison of measured resistivity for a thick sand and a thin shell.

Table 1.—*Electrode Spacing and Depth of Penetration*

Curve No.	Electrode Spacing, In. r	Electrode Spacing, In. r'	Depth of Penetration (D.P.), Ft.
1	5	600	0.83
2	10	600	1.64
3	15	600	2.43
4	20	600	3.22
5	25	600	4.00
6	35	600	5.50
7	40	600	6.20
8	47	600	7.30
9	63	600	9.50
10	89	600	12.90

difference is caused by circulating the mud before running the electric-log survey. The salinity of the interstitial water was assumed to be the same as the salinity of the produced water (1575 grains per gal.).

in Fig. 2 so that absolute values of resistivity could be measured at any depth.

As already explained, each curve is a measure of the formation resistivity, using different penetration depths. The majority

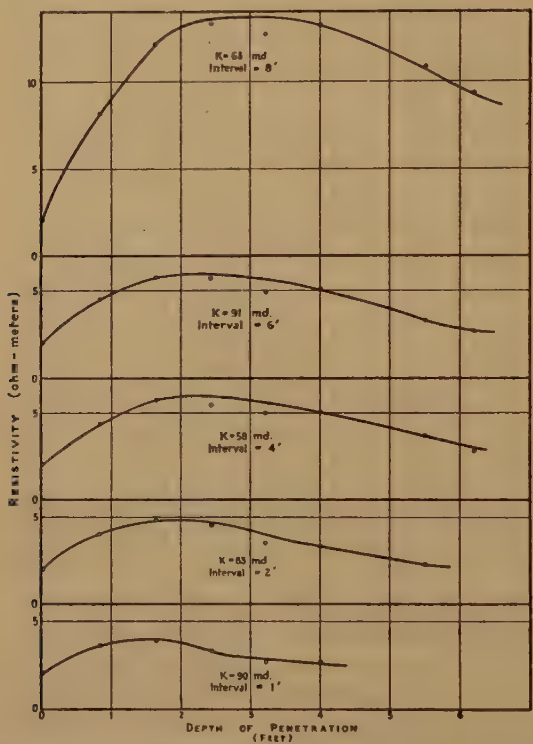

FIG. 4.—RESISTIVITY VS. DEPTH OF PENETRATION FOR AND BODIES OF DIFFERENT THICKNESSES.

TABLE 2.—*Pertinent Data*

AT TIME OF SURVEY

Formation temperature, 188°F.
Mud resistivity, 4 ohms per meter, temp. 77°F.
Mud resistivity, 2 ohms per meter, temp. 160°F.
Mud loss, 4.3 cc. 5–15 min.
Mud weight, 76 lb. per cu. ft.
Mud salinity, 35 grains per gal.

ON COMPLETION

Production index, 1.0
Static pressure, 300 lb.
Gas-oil ratio, 3700
Initial cut, 37.0 per cent
Salinity, 1575 grains per gal.

Curves corresponding to electrode spacings tabulated in Table 1 were arranged of the data used in the following correlations were obtained from Fig. 2 by measuring values of resistivity for a sand from the respective curves and repeating this procedure for all the sand bodies cored and analyzed. On plotting the value of sand resistivity for each electrode spacing with the corresponding depth of penetration, a typical curve was obtained (curve I, Fig. 3).

RESISTIVITY-PENETRATION DATA AND PERMEABILITY CORRELATIONS

Point A in Fig. 3, curve I, is the resistivity of the mud corrected for temperature.[8]

With greater depths of penetration the values of resistivity increase until B is reached. This increase in measured resistivity is caused by the decreasing

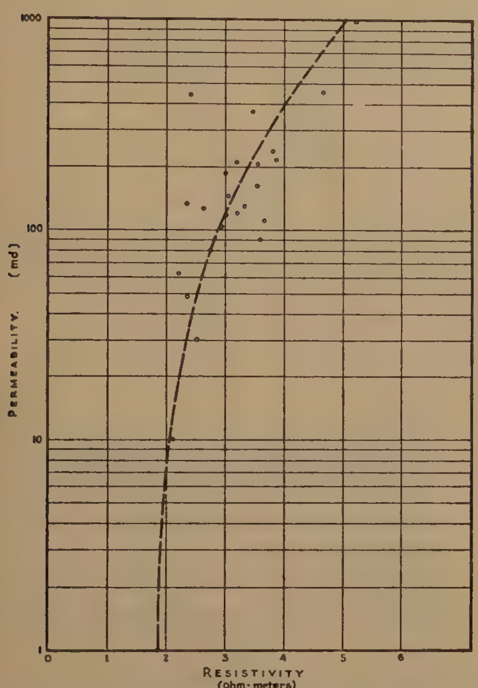

FIG. 5.—PERMEABILITY-RESISTIVITY RELATION FOR 5-INCH ELECTRODE SPACING AND AVERAGE SAND THICKNESSES OF 0.75 FEET.

influence of the fluid in the borehole as a result of greater penetration depths, and also by the infiltration of fresh water which displaces some oil and dilutes the salinity of the interstitial water. Infiltration of fresh water tends to increase the measured resistivity above the sand resistivity approximated by the value at C. Curve II, Fig. 3, is a comparison to scale of the increase in resistivity with depth of penetration for a thin calcareous shell. In coring this interval there was some lost recovery of the shell, therefore its thickness was estimated from the shallow penetration curve of the electric log. The dotted line to the point D is an estimate of what would have been recorded for a shell of substantial thickness (Fig. 3, curve II). The decrease in the measured curve for resistivity along E is due to an averaging with adjacent bodies having

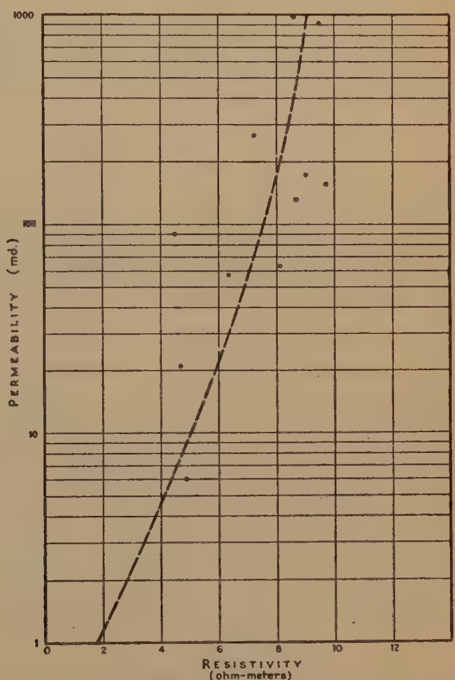

FIG. 6.—PERMEABILITY-RESISTIVITY RELATION FOR 5-INCH ELECTRODE SPACING AND AVERAGE SAND THICKNESSES OF 6.8 FEET.

a lower resistivity.[9] A more detailed discussion of the thickness factor curve will follow later. In Fig. 4, a number of curves for resistivity versus depth of penetration for sand bodies of varied thickness but of nearly the same average permeability are plotted. The maximum position of resistivity on the curves shifts to shallower penetration depths for the thinner sand bodies. This shift is not a true measure of the relative penetration of the infiltrated fluid, but is again the averaging effect of adjacent bodies of lower resistivity. Decrease in resistivity of a thick sand as illustrated by curve I, Fig. 3, where the position of the peak on the penetration curve is less than one-half the thickness of the sand

body, establishes the limits of penetration of the mud filtrate. This is because the sand body is so thick that the influence of adjacent bodies with low resistivity are of minor importance.

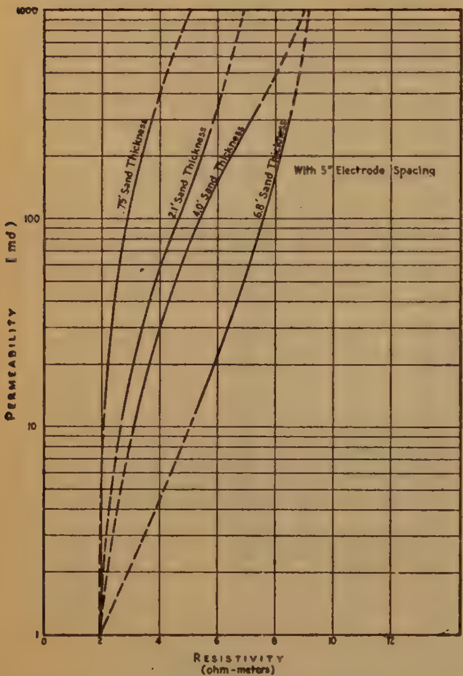

FIG. 7.—PERMEABILITY-RESISTIVITY RELATION FOR 5-INCH ELECTRODE SPACING AND AVERAGE SAND THICKNESSES OF 0.75, 2.1, 4.0 AND 6.8 FEET.

Fig. 4 is a plot of penetration curves for several sand bodies having comparable permeability and differing in sand thickness. At a common penetration the values of resistivity become increasingly large for the thicker sands. With permeability constant, this would suggest that measured resistivity is a function of sand thickness. Since interstitial water saturation is a function of permeability, as established by Schilthuis,[4] and resistivity is a function of saturation, measured resistivity is then a function of sand thickness and permeability. To establish these correlations it becomes necessary to keep one of the variables constant. In the following analysis the sand thickness is held constant.

In Figs. 5 and 6 are illustrations of the scattering of points when an electrode spacing of 5 in. and sand thicknesses of 0.75 and 6.8 ft. are used.

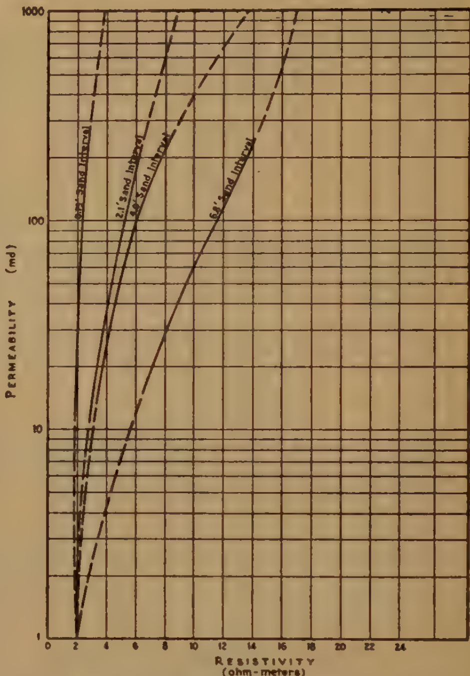

FIG. 8.—PERMEABILITY-RESISTIVITY RELATION FOR 20-INCH ELECTRODE SPACING AND AVERAGE SAND THICKNESSES OF 0.75, 2.1, 4.0 AND 6.8 FEET.

Fig. 7 is a composite of this type of curve for all the sands considered. In the construction of the curves they appeared to converge. A permeability of 1 md. and an average resistivity for 10 shale bodies of varied thickness was chosen as the point of convergence.

The permeabilities of the shales are not known, so the curve could have ended at 0.1 md. or 0.01 md. In either case this would cause little change in the curves at larger values of permeability. The regions of uncertainty are therefore drawn as broken lines. The average number of

permeability samples obtained per plotted point were 1.07, 1.83, 2.72, and 4.4, respectively, for the sands 0.75, 2.1, 4, and 6.8 ft. thick. An arithmetic average was used in commonly referred to in California as the normal electrode spacing (Fig. 8). This again shows a composite of the several sands considered.

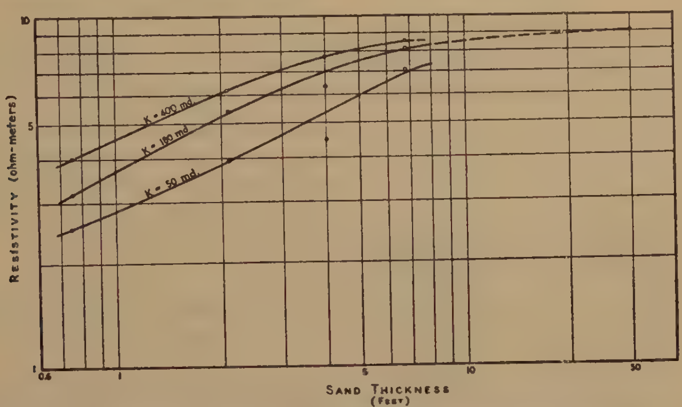

FIG. 9.—RELATION BETWEEN RESISTIVITY AND SAND THICKNESSES USING 5-INCH ELECTRODE SPACING.

every case for determining the permeability. In a number of instances this included a very wide range of individual permeability values and it is believed that a portion of the scattering in Fig. 5 is due to an insufficient number of permeability values (per

The measured resistivity value taken from the curves with this electrode spacing lies below the plotted trend on nearly all the resistivity-penetration curves, Fig. 4, D. P. = 3.22 ft. It was necessary therefore to choose a value of resistivity from the trend

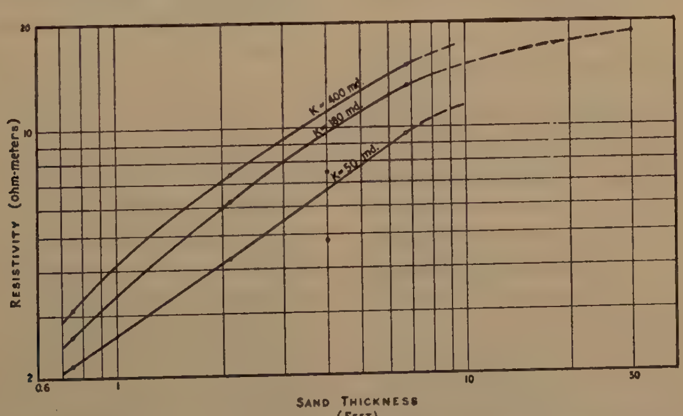

FIG. 10.—RELATION BETWEEN RESISTIVITY AND SAND THICKNESS USING 20-INCH ELECTRODE SPACING.

plotted point). To supply the present core-analysis data, 286 samples were taken for the testing of permeability, porosity and saturation. Another correlation was constructed using 20-in. electrode separation, rather than that measured. It became evident that a correlation with the 20-in. spacing would not be as good as that with the 5-in. spacing. This can be illustrated best by referring again to Fig. 4, where the values

for 0.75-ft. and 2.1-ft. sands are chosen on the decreasing side of the resistivity curve while the value on the 8-ft. sand is taken from the peak of the curve.

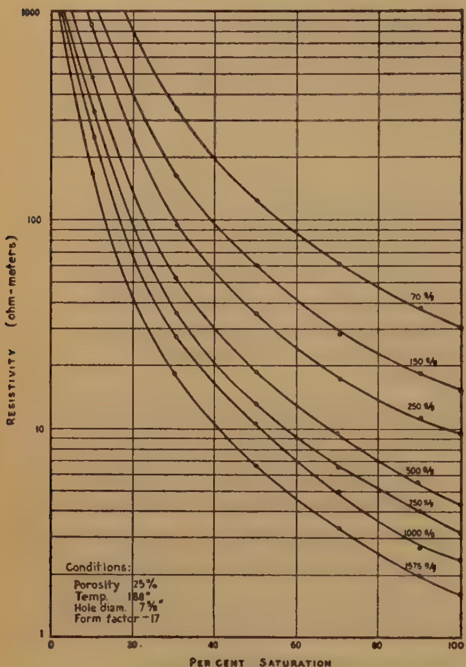

FIG. 11.—CALCULATED RELATION BETWEEN RESISTIVITY AND PERCENTAGE OF SATURATION.

The curve of the 4-ft. sand in both Fig. 7 and Fig. 8 lies too close to that of the 2-ft. sand. Original data on the 4-ft. sand did not correlate as well as those for the other sands, therefore its present position may be in error. A cross plot of the curves in Figs. 7 and 8 at constant permeability are shown in Figs. 9 and 10.

For a permeability of 180 md. the curve was extended to 30 ft. Here again the points of the 4-ft. sand appear low. The trend of the 180-md. curve influences the construction of the 50-md. curve whereby little value is placed on the 4-ft. point. These curves illustrate the effect of thickness on the measured resistivity of a sand. The increased slope of the curves for a 20-in. electrode spacing as compared with the curves for a 5-in. electrode spacing probably is caused by the greater influence of mud resistivity on the shallow 5-in. penetration.

It should be remembered that the curves for the 5-in. and 20-in. electrode spacings are made from electric-log surveys in a single well. Since the measured resistivities are for shallow penetrations, the curves are subject to change through the effect of mud resistivity and size of the well bore. In the use of these curves consideration must be given to these factors.

Calculation of Water Saturation for Several Sands

So far this discussion has dealt largely with an analysis of the depth-penetration curves in the region of infiltration. To determine water saturation of large sand bodies from resistivity it is necessary to know the relation between sand resistivity and water saturation. A series of theoretical curves (Fig. 11) was constructed to offer this utility, and these curves are now being checked by laboratory tests. A formation factor was calculated for shales:

$$F = \frac{\text{resistivity of shale (assumed 100 per cent saturated)}}{\text{resistivity interstitial water}} = \frac{1.8}{0.105} = 17$$

Measured resistivity of the interstitial water at 188°F. agrees closely with the calculated value. It was possible therefore to determine with accuracy the resistivity of water having salinities of 70, 150, 250, 500, 750 and 1000 grains per gal. The values of resistivity for these salinities were multiplied by the formation factor, which gave the resistivity of a sand characterized by 25 per cent porosity and 100 per cent saturation. The trend of resistivity with saturation was then determined from the curves developed by Martin,[5] Jakosky,[6] Wyckoff,[7] and Leverett,[8] which relate the change in percentage of saturation of a

sand to the percentage of original conductivity at 100 per cent saturation. Before applying the curves in Fig. 11 to the measured values of resistivity, it was obtained by inserting the corrected resistivity on the curve for 1575 grains per gal. salinity in Fig. 11. These are the values listed as S_2 in Table 3. In order to weight

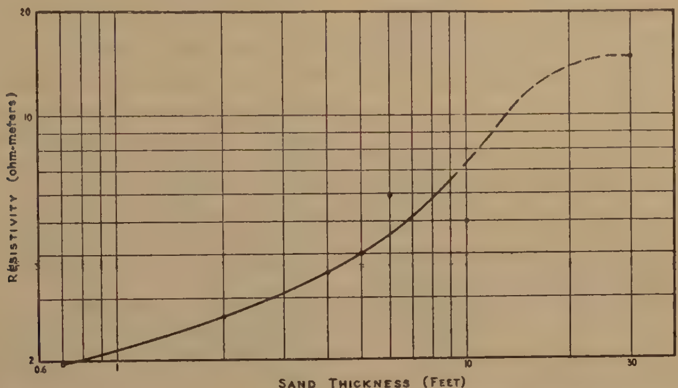

FIG. 12.—RELATION BETWEEN RESISTIVITY AND SAND THICKNESS WHEN SAND PERMEABILITY IS 180 MILLIDARCYS AND ELECTRODE SPACING 63 INCHES.

necessary to devise an empirical curve that would correct the resistivity for thin sand bodies. A tentative curve was constructed for an average permeability of 180 md. and an electrode spacing of 63 in. (Fig. 12). Because the data were incomplete, the curve has regions of approximation, but for the thinner sand bodies individual points are weighted values and line up on a smooth trend. A curve of thickness factor (Fig. 13) was constructed from Fig. 12.

It is assumed in this construction that the resistivity of the 30-ft. sand is correct and that thickness factors were determined for the thinner sands, so the product of the measured resistivity times the thickness factor equals the true resistivity of the sand. It is believed that the curve for thickness factor can be applied to sands of different permeability with reasonable accuracy. A trial solution was made for a number of cored sands for which the values of permeability were measured (Table 3). Calculations for saturations in Table 3 use the measured resistivity at a penetration of 9.5 feet.

Individual water saturation can be the saturation values for the above eight sands, it was necessary to consider the influence of permeability and sand thickness. The weighted interstitial saturation

TABLE 3.—*Calculated Saturation of Eight Sands*

Sand Thickness t, Ft.	Permeability K, Md.	Critical Saturation S_1, Per Cent	Measured Resistivity 9.5 Ft. D. P.	Thickness Factor, T. F.	Corrected Resistivity, Ohms per Meter	Calculated Saturation S_2, Per Cent
30	180	24	14.6	1	14.6	34
7	977	21	14.35	2.8	40.2	20
5	173	24	4.0	3.6	14.4	34
6	131	26	4.66	3.15	14.7	33
6	91	27	1.8	3.15	5.66	54
7	63	29	5.34	2.8	15.0	33
10	263	23	5.06	2.06	10.4	40
9	57	30	4.0	2.26	9.1	43
	18,021	4,182				5,473

$$\text{Interstitial water} = \frac{4182}{18021} = 23.2 \text{ per cent}$$

$$\text{Calculated saturation} = \frac{5473}{18021} = 30.3 \text{ per cent}$$

Initial cut of well = 37 per cent

was determined by taking the sum of the products of sand thickness times permeability times saturation and dividing

by the sum of the products of thickness times permeability. A similar calculation was made for the resistivity saturation S_2.

Conclusion

The results of the tests present a relative term depth of penetration for comparing

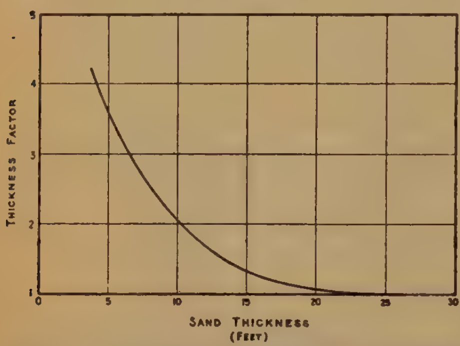

FIG. 13.—RELATION BETWEEN THICKNESS FACTOR AND SAND THICKNESS.

the respective amounts of the formation measured for changes in electrode spacing. By means of this term it becomes possible to construct a resistivity-penetration curve that can be divided into two regions of analysis. First, the portion of the resistivity curve that is affected by the presence of drilling fluid, and second, the value of resistivity measured beyond the influence of the drilling fluid. Correlation for infiltrated portion of the sand represents resistivity as a function of permeability at a constant sand thickness. The cross plot of these data illustrates the very large effect sand thickness has on the measured resistivity. Therefore, it is possible for a thick sand body of low permeability to record a higher resistivity than a thin sand of high permeability.

In the analysis of the second portion of the resistivity curve, calculations are made for the percentage of water saturation by choosing values of resistivity measured beyond the effect of mud infiltration. To do this it was necessary to construct a curve relating sand resistivity to the percentage of saturation. For the thinner sands, a thickness-factor curve aided in correcting the measured resistivity for sand thickness. Calculations were then made on eight sands cored in the well, which differ in thickness and permeability.

After weighting the saturations for thickness and permeability, it was seen that the calculated saturation is greater than the critical saturation. This would suggest that these sands would initially produce some water.

Acknowledgment

The author wishes to express his sincere appreciation to Mr. Howard C. Pyle for directing the work, and to Messrs. John E. Sherborne and Stewart Hagestad, of the Union Oil Company of California, and John C. Stick, Jr., of the Lane Wells Corporation, for their generous help in performing the tests; also to the Union Oil Company of California for its release of the data presented.

References

1. Archie: *Trans.* A.I.M.E. (1942) **146**, 54.
2. J. C. Stick Jr.: By letter of correspondence.
3. Sherborne and Newton: *Trans.* A.I.M.E. (1942) **146**, 204.
4. Schilthuis: *Trans.* A.I.M.E. (1938) **127**, 199.
5. Martin, Murray and Gillingham: *Geophysics* (July 1938).
6. Jakosky and Hopper: *Geophysics* (Jan. 1937).
7. Wyckoff and Botset: *Physics* (Sept. 1936) 325.
8. Leverett: *Trans.* A.I.M.E. (1938) **132**, 149.
9. Zaba and Mounce: Drill. and Prod. Practice, Amer. Petr. Inst. (1940).

DISCUSSION

(J. E. Sherborne presiding)

J. C. STICK, JR.,* Los Angeles, Calif.—It is generally recognized that there is a great deal more information contained in electrical logs than is utilized in their normal use. This has resulted primarily from the lack of available data on the behavior of the several variables incorporated in the electrical measurements. The complex nature and interdependence of these variables has greatly complicated their study from the standpoint of obtaining quantitative data on the magnitude of their effects.

* Lane-Wells Company.

The series of experimental runs from which Dr. Zinszer derived his data were made to study the practical aspects of the effects of these variables and to determine as many empirical relationships as possible between the electrical and physical properties of formations. The results of this study appear to substantiate the possibility of deriving useful relationships between the permeability and fluid saturation of formations and their resistivity as indicated on the electrical log.

The establishment of such relationships is dependent not only on their existence but on the accuracy with which the various parameters can be measured and with which correction factors can be determined and applied. The necessity of obtaining the average of the permeability and porosity values for many sands is recognized as a possible source of error even in a well where core analysis is utilized extensively.

The determination and application of thickness factors are very important in analysis of the resistivity response. The effect of electrode spacing on formation response is clearly illustrated by the series of runs at progressively increasing depths of penetration. For example, the three sands indicated on the 5-in. spacing curve between 5875 and 5890 ft. are resolved into two and then into one sand with increasing depths of penetration. The empirical determination of thickness factors requires careful selection not only of strata of equivalent physical characteristics and thickness but of formations that are sufficiently isolated not to be influenced by the presence of others. The use of these factors must be governed by similar considerations.

The utilization of thickness factors is very important in the analysis of the resistivity curve response. The application of these factors requires careful selection. The utilization of thickness factors is very important in the analysis of the resistivity curves. The application of these factors requires careful consideration of the particular strata to determine the effects of surrounding formations. This is especially true of the thinner beds. For example, the three sands indicated on the 5-in. spacing curve between 5875 and 5890 ft. are resolved into two and then into one sand with increasing depths of penetration. The application of thickness factors to such zones may incorporate considerable error.

G. Potapenko, Pasadena, Calif.—Dr. Zinszer assumes the depth of penetration to be represented by the equation

$$D.P. = \frac{2rr'}{r + r'} \qquad [1]$$

where r and r' are the distances between the pick-up electrodes and the power electrode C_1 (Fig. 1).

It could be shown that the depth of penetration depends upon both r and r' only when approximately

$$r' - r \leq \frac{r + r'}{12} \qquad [2]$$

When this condition is not fulfilled, the potential at the distance r' from C_1 is negligible compared with the potential at the distance r. In such case, the depth of penetration is independent of r', and it may be taken to be approximately equal to r. The data of Table 1 show that in all cases with which Dr. Zinszer deals

$$r' - r \gg \frac{r + r'}{12} \qquad [3]$$

Therefore, Eq. 1, which he uses to calculate the depth of penetration, is inapplicable to his cases, and the curves of Figs. 3 and 4 should be replotted taking r as abscissa. Eq. 1 at $r' \gg r$ goes over into $D.P. = 2r$. Therefore, the suggested change of scale is approximately equivalent to dividing by 2 the depth values indicated in Table 1 and on Figs. 3 and 4.

It is well known that the resistivities calculated from logging data depend upon the ratio of the electrode spacing to the diameter of the hole, especially when this ratio is small, as with 5-in. spacing. Because of this a curve such as is shown in Fig. 13 should be taken to be valid for the given hole diameter only, and it would be of great interest if the thickness factors could be determined for holes of various diameters.

The S. P. Dipmeter

By H. G. Doll,* Member A.I.M.E.

(Austin Meeting, October 1942)

This paper discusses a method and apparatus for determining the dip of formations traversed by a drill hole, by means of electrical measurements in the hole. The process consists in recording the Spontaneous Potentials present along three oriented generatrices in the hole. By comparison of the three curves thus obtained, after application of a correction factor to compensate for any deviations of the hole, the dip angle and the dip direction are determined. Excellent accuracy is obtained for dip angles over 10°.

Because the method is simple and the apparatus rugged, the measurements are rapid and reliable; consequently, they can be made at all the levels that are of interest at any time after the well has been drilled. Mechanical cores are not needed to evaluate the dips.

A convenient, time-saving procedure is to perform the dipmeter survey at the time the electrical log is taken, using for both operations the same cable and truck.

Actual examples of results obtained in wells of the Gulf Coast area are given.

Introduction

The problem of determining the angle and direction of the dip of the strata traversed by a drill hole has practical interest, and sometimes vital importance, which need not be emphasized to the oil industry. The need for that type of information has existed ever since wells have been drilled. Certainly it has not subsided, in spite of the numerous inventions and improvements made in other fields of the art of drill-hole exploration. The few examples given in this paper are but illustrative of this fact.

In the past, methods have been devised, and used, to solve this problem, but generally they have met with limited success, possibly because they failed more or less to answer the requirements of a modern age for fast yet accurate measurements. If accurate, the results were obtained at the cost of very tedious and lengthy operations.

The new S. P.* dipmeter service offered to the oil industry is the result of exhaustive research in this particular field. In 1932 a dipmeter and electromagnetic teleclinometer service was made available. The apparatus employed then was of a rather delicate and costly construction, and the measurements had to be made with precautions sometimes difficult to secure on the rig. Although the information given by the electromagnetic dipmeter was limited to the direction of the dip, very interesting results were obtained in California, Trinidad, Venezuela, Rumania and, most notably, in the Netherlands East Indies.†

Apparatus

The S. P. dipmeter surveys present none of the drawbacks mentioned above. The apparatus is rugged and free from constructional complications, therefore well adapted to field use. This, combined with the new, basically simple approach to the problem, explains the rapidity of execution of the measurements. The results are remarkably accurate and they are complete, giving the

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* Director of Research, Schlumberger Well Surveying Corporation, Houston, Texas.

* Spontaneous Potentials.

† References are at the end of the paper.

dip angle as well as the dip direction. As these surveys have made much headway in field practice since their recent launching, it seemed timely to offer a brief description of the apparatus and method involved. In the light of the results actually obtained, some of which are included in this paper, an attempt is also made to visualize some of the far-reaching possibilities of this new development.

Dip determinations are often made by geologists in a general way by taking electrical logs in at least three wells not in a straight line and by establishing correlation between the logs. The correlation lines passing through the same formations in the three wells define the plane of the formations; hence the average dip is ascertained. This method discounts the possibility of geological disturbances occurring between the wells; besides, the main practical drawback of the method is that three logs should be available—i.e., three wells must have been drilled and logged.

The S. P. dipmeter* utilizes a somewhat similar idea, but it requires only one well, in which the three logs are simultaneously recorded. The measurements are made by means of three independent electrodes (1, 2 and 3) spaced at 120° angles in a plane perpendicular to the axis of the instrument (and of the hole), and situated on a circle of a known diameter corresponding to that of the hole, so that the electrodes are always in fairly close contact with the walls of the hole (Fig. 1). The orientation of the electrodes is given by a photoclinometer, another purpose of which is to disclose the inclination and orientation of the drill hole at the point of location of the instrument. The photoclinometer is thus an indispensable adjunct of the dipmeter.

The logs recorded by the three electrodes make possible (as will be shown in more detail hereafter) accurate determination, in the uncased part of the drill hole, of three points of the boundary plane separating two beds of different natures; for instance, a permeable bed and an impermeable one. These three points, being oriented by the photoclinometer, suffice to determine completely the plane in question.

The great accuracy that is necessary in view of the short distances between electrodes is secured by recording the three logs simultaneously and by holding the

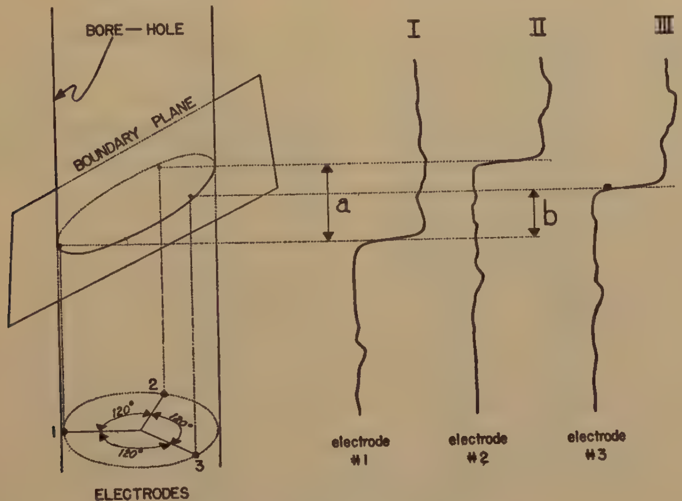


FIG. 1.—S. P. DIPMETER CURVES.

* U. S. Patent No. 2176169, issued Oct. 17, 1939.

electrodes and orienting apparatus in fixed relative positions.

In practice, the electrodes are little disks mounted on three resilient supports, which

FIG. 2.—S. P. DIPMETER ASSEMBLY.

in turn are mounted on a rigid elongated body. The supports also serve as guides for the instrument and keep its orientation virtually constant when it is moved in the hole (Fig. 2). Each of the electrodes is connected through an insulated conductor to a separate potential-measuring device at the surface of the earth, its circuit being closed through the earth and a ground electrode (Fig. 3).

Generally on top of the dipmeter (Fig. 2), and always in the same relative orientation, is placed the photoclinometer. This instrument, already well known in the industry, combines in one body a compass needle and a clinometer consisting of a ball

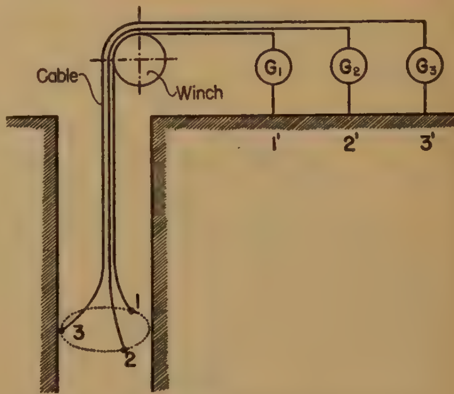


FIG. 3.—POTENTIAL-MEASURING DEVICE.

free to settle in equilibrium position on a graduated glass of known curvature. In that same body is a camera capable of taking pictures of the needle and of the ball. On the picture also appears a marker showing the orientation of electrode 1, which may be called the reference electrode (Fig. 4).

The photoclinometer is purposely made long. It has centering guides, so that its axis coincides with that of the hole. The position of the clinometer ball, therefore, is a measure of the inclination of the well, and the compass needle gives the bearing of that inclination. These two elements make possible the determination of the correction to be made on the dip as measured by the S. P. dipmeter.

The surface equipment comprises one control-panel box of small dimensions (Fig. 5) containing the switches and dials and instrument controls that govern, entirely from the surface, the taking of the photoclinometer pictures, and the operation of the S. P. dipmeter. The galvanometers and the film of the recorder used for the standard electrical surveys serve for the recording of the S. P. dipmeter logs.

OPERATION

The operation of the S. P. dipmeter is based on a now well-known phenomenon; namely, the fact that the spontaneous potential measured by an electrode in the uncased part of a well varies in an abrupt manner when that electrode traverses the boundary plane between a permeable stratum and an impermeable one. This phenomenon is being recorded simultaneously but independently, as previously mentioned, by the three electrodes of the dipmeter, which for that purpose is made to travel along the hole and to traverse the boundary plane in question. The three separate S. P. logs thus recorded—preferably on a very large depth scale—will be found, of course, to be substantially alike, but they are different in one important respect—the abrupt changes corresponding to the passage of the electrodes from the impermeable bed to the permeable bed (or vice versa), are not recorded at exactly the same depth. The discrepancies in depth observed precisely correspond to, and are a measure of, the dip of the boundary plane separating the two beds, and consequently of the beds themselves.

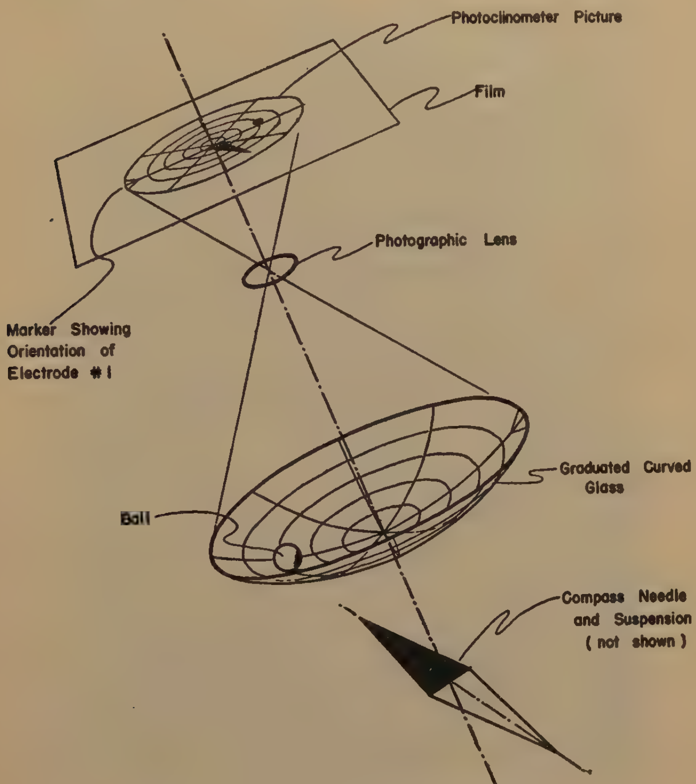


FIG. 4.—ELEMENTS OF PHOTOCLINOMETER.

It should be clear that other characteristics of the formations capable of showing a clearly distinguishable change when a change in formation occurs could be used instead of the S. P. for such determinations. For instance, a "resistivity dipmeter" might be conceived.

In practice, three S. P. logs are obtained as shown on the right side of Fig. 1, and the discrepancies in depth (*a*) between refer-

ence electrode 1 and electrode 2, and (*b*) between electrodes 1 and 3, can be measured. If the well is strictly vertical, the knowledge of: (1) the diameter of the circle on which the electrodes are situated, (2) the quantities (*a*) and (*b*), and (3) the orientation or bearing of electrode 1, as revealed by the photoclinometer picture, permits an immediate and very simple determination of the dip angle and bearing of the boundary plane.

In the majority of cases the well is not vertical and the determination of the boundary plane is not quite so simple. Allowance then must be made for the inclination and orientation of the well. Nevertheless, the determination is very rapid, either by purely geometric construction or by computation.

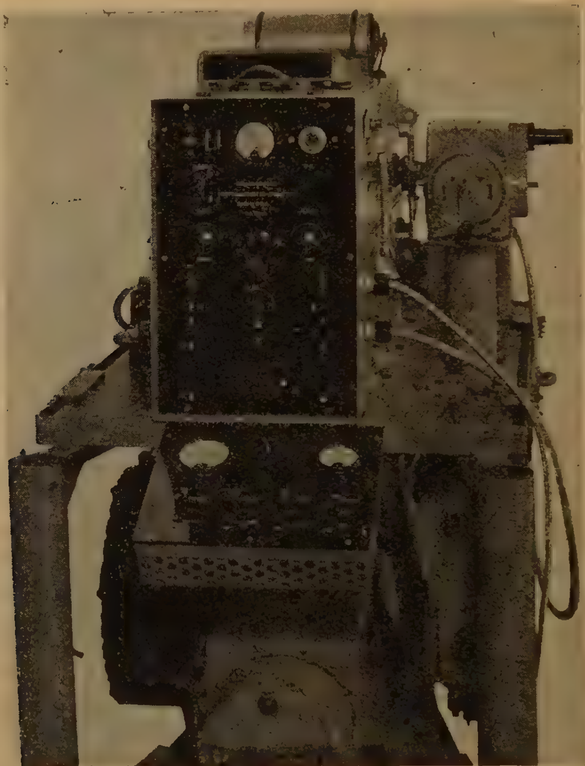


FIG. 5.—CONTROL PANEL AND PHOTOGRAPHIC RECORDER.

A special apparatus (Fig. 6) has been designed* for making a physical reconstruction of the elements found in the drill hole at the level under consideration. By means of this apparatus, the measurements obtained can easily and quickly be translated into terms of dip angle and direction of dip.

In practice, the survey of a horizon follows a series of simple steps, which may be described as follows: The dipmeter-photoclinometer assembly is lowered down the hole until it is some distance (10 to 15 ft.) below the desired section. The S. P. is observed all the way down, so as to make sure of the movement of the instrument. The latter is then pulled up to about 3 ft.

* Developed by Owen H. Huston, Research Department, Schlumberger Well Surveying Corporation.

below the section and stopped there. After a short interval of time, to allow the instrument to settle, a picture is taken by the photoclinometer. This done, the section is surveyed by the three dipmeter electrodes. At the upper end of the section, a second photoclinometer picture is taken, which (besides giving the orientation and inclination of the well at that point) permits the operator to ascertain that the assembly has not rotated while it was being pulled up. The instrument is then lowered below the section, and all the steps and measurements are repeated in the same order as before.

Generally, more than one horizon is studied, and an S. P. dipmeter survey will comprise as many S. P. logs and photoclinometer determinations at as many levels as are deemed necessary to furnish the data desired.

FIG. 6.—INSTRUMENT FOR INTERPRETATION OF MEASUREMENTS.

EXAMPLES

The results presented show for all the levels or stations studied: (1) the pictures of the photoclinometer, (2) the S. P. logs recorded by the three electrodes, (3) a table, which converts into numbers the pictures and logs, showing on one hand the elements of drift of the well (angle and bearing) and on the other the elements of the dip, corrected to vertical (angle and bearing).

In example A (diameter of hole, 9⅞ in.) the photoclinometer was equipped with a clinometer glass capable of measuring drift angles up to a maximum of 15°. The pictures of the ball and compass needle (Fig. 7) projected on a screen reveal that the aver-

age drift of the well in the section considered (9440 to 9470 ft.) is 5° 20′, and that the azimuth of this drift, from magnetic north, is 156°. Furthermore, the pictures shifting, the value and direction of which are noted. In the case at hand, curve II had to be shifted up by 5.0″ to superimpose on I. This means that electrode 2 recorded the

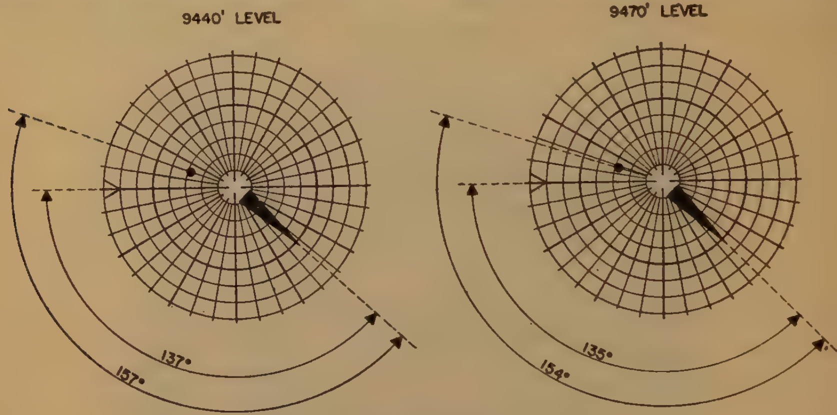


FIG. 7.—PHOTOCLINOMETER PICTURES.

show that electrode 1, and consequently the assembly, rotated by about 2° while the assembly was pulled up from 9470 to 9440 ft.—which is quite satisfactory. The average orientation of electrode 1 is measured to be 136° from the magnetic north.

In a study of the logs (Fig. 8A), two transparent copies of the figure should be available. The aim is to obtain the best superimposition of curves II and III (electrodes 2 and 3, respectively) on curve I, which is taken as reference curve. This result is achieved after a certain amount of change in formation 5.0″ before electrode 1 did; therefore the strata were dipping down from electrode 1 toward electrode 2. This is reported in Table 1. Similarly, the strata are found to dip down from electrode 1 to electrode 3 by 9.8″. From these elements, it is possible to find the value of the dip and its direction by geometric construction or with the help of the apparatus shown on Fig. 6. The direction can be reported either as 341° (clockwise from magnetic north), or N. 19 W. (19° from magnetic north in the west quadrant). All this information is summarized in Table 1.

TABLE 1.—*Examples*

Sta. No.	Depths, Ft.	Azimuth Well F.M.N.	Well Drift	Orientation Electrode No. 1 F.M.N.	S. P. Curves			Angle of Dip	Direction Formation Dip	
					I	II	III		F.M.N.	F.G.N.*
				EXAMPLE A						
A	9,440 9,470	156°	5° 20′	136°		D5.0″	D9.8″	54°	N. 19° W.	N. 25° W.
				EXAMPLE B						
A	10,630 10,600	327°	3°	258°		U3″	U3″	21°	254°	261°

* From Geographic North.

In example B (diameter of hole 9⅝ in.), the discrepancies in depth between curves II and III, on the one hand, and curve I, on the other, happen to be the same and equal to 3″; as to direction, the strata rise from electrode 1 toward electrodes 2 and 3 (Fig. 8B). (See Table 1.)

In these two examples, the discrepancies in depth, and consequently the dip, could be measured with a great degree of accuracy, mostly because the dip was large enough to make the discrepancies large, partly also because the changes in the curves were fairly sharp. When the dip is much smaller, a correct measurement of the absolute values of the discrepancies may become difficult, but a correct estimate of the sign of these discrepancies is almost always possible. In other words, for very small dips, the angle of dip cannot be given with accuracy, but its general orientation can.

It can readily be seen that the accuracy of the measurements will vary according to the value of the dip angle, the sharpness of the breaks in the recorded curves, and the size of the dipmeter apparatus, which depends on the hole diameter. Under normal conditions in the Gulf Coast territory, it has been found that the accuracy is very good for dip angles of 10° or above; between 5° and 10° reliable determinations can be made when other conditions are favorable; around 5° it is sometimes possible to give the general direction of the dip. Fortunately, it often happens that less accurate and complete information is required from dip measurements in the case of low dips than for steep ones. This fact is substantiated by the following discussion of some of the possibilities and practical applications of the instrument.

Applications of Instrument

This paper does not discuss in detail the possibilities of dip measurements in oil-field practice. It is well known that dip determinations are of value when all types of geological structures favorable to oil accumulation are being drilled, from the familiar types of anticlines and domes to

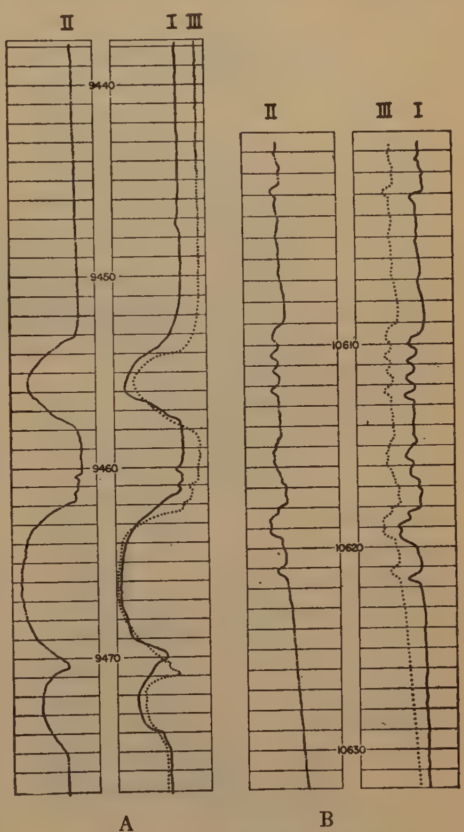


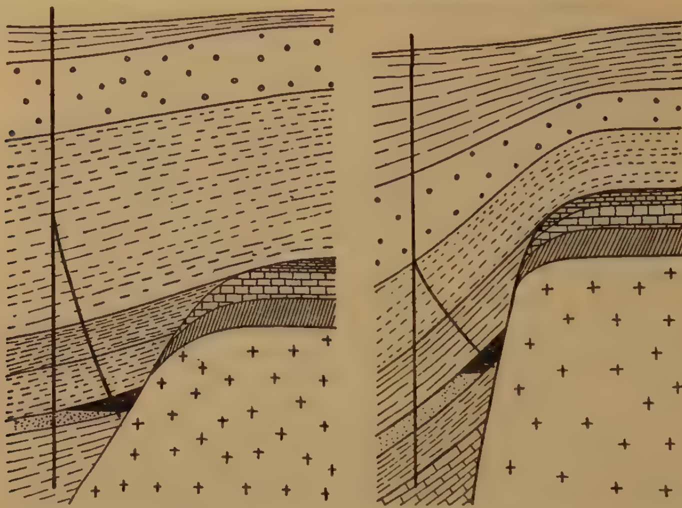
Fig. 8.—S. P. dipmeter curves.

monoclines, faults, and unconformities. However, it should be kept in mind that the use of the S. P. dipmeter offers some possibilities heretofore practically impossible to attain.

With the new apparatus, dip determinations can be made at any level in an open hole after it has been drilled, whether or not cores are available. The S. P. dipmeter survey can be performed at the time the electrical log is taken, the information thus obtained naturally supplementing the information given by resistivity and S. P. measurements. Obviously this is a conven-

ient and a relatively cheap way to obtain quickly data that could be had only while drilling by means of mechanical cores cut and examined under special conditions.

that structures usually are more complicated than expected; geological cross sections often are revised after a number of holes have been drilled. There is no doubt



a *b*

FIG. 9.—EFFECT OF DIP ANGLE ON DEVIATION OF SIDE TRACK.

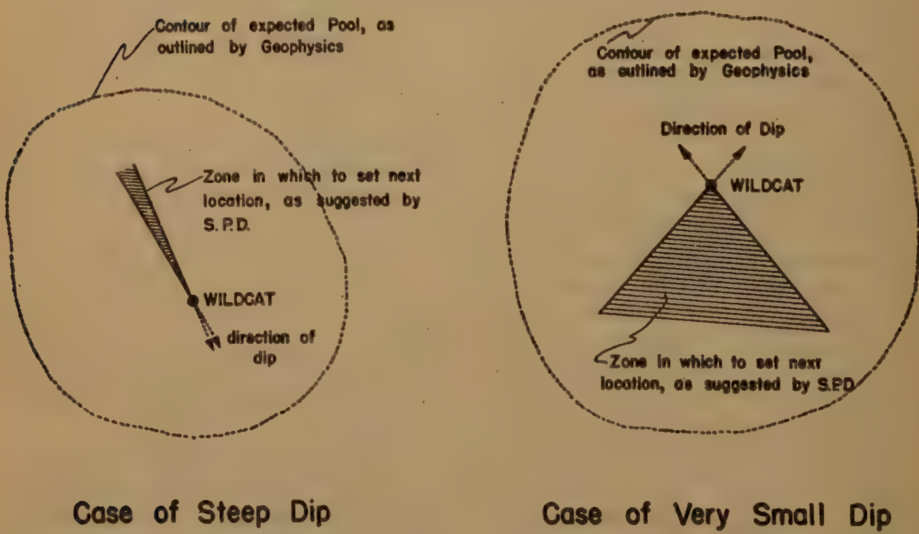


FIG. 10.—SECTORS IN WHICH TO DRILL WELLS.

Another point of great importance is that numerous determinations can be made accurately in a short time and at many depths in a drill hole. Experience has shown

that a better knowledge of the dip at the time the first few wells are drilled would greatly help in the future drilling program, giving to the geologist and to the produc-

tion engineer, in the first stage of development of a new field, a more complete picture of the conditions underground. Dip measurements made at relatively short intervals in the hole will often show that the dip angle or the dip direction changes with depth. This indication permits better definition of the subterranean contours roughly outlined by geophysical means, with the certainty attainable only with measurements *in situ*, and an ease that leaves other methods far behind.

Just as important as the correct definition of subterranean contours, and a prerequisite to the evaluation of the oil reserves in a given field, is the determination of the true thickness of the producing horizon (or horizons). It will be obvious that in some structures (such as domes of the piercement type, for instance) where steep dips must be expected a correction factor dependent upon the dip must be applied to the apparent thickness given by the electrical logs or the driller's logs. The S. P. dipmeter readily supplies this indispensable correction factor.

When the first well of a new prospect happens to be a dry hole, the problem that confronts the development men is to determine in which direction to side-track or to drill the next well. That question also is answered by the dipmeter. The dip measurement will further help to select the side-track angle. This is illustrated for a piercement dome in Fig. 9. If the dip is found to be small, a little deviation of the original hole offers a good chance to hit the oil, without hitting the salt dome. On the contrary if the dip is very steep, it will be necessary to deviate the original hole a great deal. The same comments apply to the case, admittedly much less frequent, of oil occurring on the flanks of a volcanic intrusion.

If the operator is fortunate enough to have a producer in his first well, S. P. dipmeter measurements, together with the production data, indicate where to set the next location, and in what direction the future field will develop. Of course, as pointed out earlier in this paper, the amount and accuracy of the information obtained from the strata are directly governed by their angle of dip. If the dip is large enough, it will be possible to answer all the questions with great precision, and particularly to restrict to a small sector of a certain quadrant the zone in which to drill the next well (Fig. 10). If the dip is very small, so that its accurate determination is difficult, only the general direction of the next location, within a quadrant or so at worst, can be given. However scanty such information may seem, it is very precious in wildcat territory, when all data at hand give such an incomplete picture of the structure.

Another application of the dipmeter, where the results already obtained are promising, is the identification of fault blocks. Not enough evidence on this complex subject is available yet, but the S.P. dipmeter measurements alone have made possible in one field the location of three faults through the identification of the adjacent blocks in several wells, each block being distinguished from the others by the angle and the orientation of its dip.

References

1. C. and M. Schlumberger and E. G. Leonardon: Electrical Coring; a Method of Determining Bottom-hole Data by Electrical Measurements. *Trans.* A.I.M.E. (1934) 110, 237.
2. C. and M. Schlumberger and H. G. Doll: The Electromagnetic Teleclinometer and Dipmeter. World Petr. Congress, London, July 1933.
3. C. and M. Schlumberger and H. G. Doll: The Electromagnetic Dipmeter and Determination of the Direction of Dip of the Sedimentary Strata Crosscut by Drillings. Int. Congress Mines, Metallurgy and Geological Technology, Paris, October 1935.
4. M. Schlumberger and H. G. Doll: Discussion of Results Obtained with the Electromagnetic Dipmeter on a Known Geologic Structure. Second World Petr. Congress, Paris, June 1937.

Natural Potentials in Well Logging

By W. D. Mounce* and W. M. Rust, Jr.,† Member A.I.M.E.

(Dallas Meeting, May 1943)

Abstract

The almost universal acceptance of electrical logging by the petroleum industry calls for a critical examination of the physical bases of the common methods. This is particularly needed for the natural potential log. The conventional explanations are based on the phenomena of electrofiltration and electroosmosis. However, experimental data show that they fail to give a basis that is quantitatively sound. Moreover, they lead to interpretations of details of electrical logs that are erroneous.

It was found experimentally that when a plug of shale is placed in a chain of dissimilar electrolytes, a current flow results. Experiments on oil-well cores and fluids similar to those existing in wells show that potentials are set up which are in reasonable agreement with those encountered in electrical logging. Doubtless other sources of potential are important but this explanation not only accounts for much of the potential but also clarifies some fairly familiar examples of misinterpretations.

Introduction

The extraordinary value of electrical well logging as a tool for petroleum engineers and geologists is now so universally recognized that it is not necessary to point out the ways in which it can be useful. It is sufficient to mention only the saving that has resulted from the elimination of much coring that would have been necessary under former practices and the considerable additions to reserves resulting from the discovery of sands missed in coring.

Paradoxically, the very remarkable success that has resulted from the application of electrical logging to correlation and completion problems has cost some of its most consistent users dearly.[1] The fact that some operators have placed unwarranted faith in erroneous interpretations of electrical logs does not reduce the value of the logs. It should, however, make one pause long enough to ask why experienced users should be misled. The answer to this question is not hard to find. In nearly every case, the fault has been oversimplification. This is illustrated very aptly by the familiar interpretation and theory of the natural potential log.

Recording and Interpreting Logs

The natural potential log is extremely simple to record precisely enough for all present-day uses. One needs only an electrode, a cable to lower the electrode through the drilling mud, a recording meter and a surface ground connection. The electrode can be elaborate but need not be. A simple brass rod 2 in. in diameter and 2 or 3 in. long is quite satisfactory. The cable need not be particularly well insulated, nor need it have a very low resist-

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* With the Naval Ordnance Laboratory, Washington, D. C., on leave of absence from the Humble Oil and Refining Co., Houston, Texas.

† Geophysics Research Department, Humble Oil and Refining Co., Houston, Texas. While most of the material and data for this paper were collected by the senior author, the junior author is responsible for the errors it may contain, since unavoidable circumstances made it impossible for the senior author to correct them.

[1] References are at the end of the paper.

ance. The recorder can be a vacuum-tube voltmeter, an automatic potentiometer or a sensitive photographically recording galvanometer, but it can be a conventional chart-type recorder. The surface ground connection can be a stake driven into the ground, a clamp on the surface casing or an electrode placed in the slush pit.

The customary interpretation is equally simple. In many areas, such as parts of the Texas Gulf Coast, where the well encounters a series of alternate strata of sand and shale, the potential log has a familiar form. It consists of a somewhat irregular base line from which there are occasional deflections of varying amplitudes, frequently with rather sharp sides and a fairly flat top. Very frequently, the "base line" is found opposite the shale sections and the deflections or "kicks" opposite the sand sections. The interpretation is, therefore, that "kicks indicate sands" and "sands are indicated by kicks." Not infrequently, some kicks do not indicate sands. This is annoying and sometimes a little expensive but not serious and can be written off as one of nature's minor vagaries. Some people may wonder why the kicks were there but the situation is not serious. It becomes serious only when it is discovered that a sand, an oil sand, was not indicated by a kick.

Theory

Electrofiltration Potential

The usual theory[2] is equally simple and is derived directly from the generalization that sands are somehow correlated with the potentials. The theory is twofold; that is, two concurrent causes are assigned to the potential, each adding its share to the observed total. The more popular explanation is "electrofiltration potential." Electrochemists have long been aware[3] that when an electrolyte is forced through a permeable dielectric a difference of potential is set up. This phenomenon has been studied extensively and the experimental data are public knowledge. The resulting potential is proportional to the pressure drop across the dielectric, the factor of proportionality depending upon the natures of the dielectric and the electrolyte. Since, for a given fluid and a given filter, the rate at which fluid flows through the filter is also proportional to the pressure drop across the filter, it follows that for a given electrolyte flowing through a given plug of a given dielectric, the potential due to electrofiltration is proportional to the rate of fluid flow. But for a given pressure drop, the rate of fluid flow is proportional to the permeability.

From these two fairly exact statements, it is possible by a simple non sequitur to derive the false conclusion that the potential due to electrofiltration is proportional to the permeability. Hence, if the natural potential log were principally the result of electrofiltration, it would be a permeability log; or, if only the electrofiltration potential were affected by changes in pressure, it would be possible to determine the permeability by making two logs at different pressures and observing the difference in the natural potential logs.[4]

Actually, the properties of the filter, which chiefly determine its effect on the electrofiltration potential, are its chemical nature and the condition of its surface. Its permeability has little or no effect. Any correlation between the natural potential log and permeability is to be explained by the fact that some of the factors that affect the permeability of a sand also directly affect the potential, as will be illustrated later. However, the theory that the potential log somehow measures the permeability of the sand is still popular. For this reason, it seems advisable to include some additional discussion on this point. Very direct evidence is given by the poor correlation* between potential logs in oil

* The classical example of the Bradford gas sand, Fig. 8 of ref. 4, is a log of a water-

wells and measured permeability of cores.[5] A factor frequently overlooked in this connection is the comparison between the permeabilities of the sand and of the filter cake that is formed on the face of the sand by the drilling mud. It has been shown by experiments[6] that the permeability of the filter cake is from 100 to 10,000 times lower than the permeability of typical oil sands, and almost entirely independent of the permeability of the sand; consequently, the resultant effective permeability of the sand and filter cake is determined almost entirely by the filter cake. Thus, if the potential log did measure permeability, it would be the permeability of the filter cake and not the unrelated and much greater permeability of the sand.

Even so, the permeability of the filter cake is higher than the permeability of the shale, so that the natural potential might be due largely to electrofiltration and thus distinguish permeable sands from impermeable sands, shales, or other materials, even though the permeability of the sand could not actually be determined. Two experiments can be cited on this point. One is a laboratory experiment;* the other, a field experiment.

In the laboratory experiment, a cylindrical core liner was placed in a radial filtration apparatus. The core was filled with a typical drilling mud and pressures ranging from 2 to 16 atmospheres were applied. The potential difference was measured between the mud being filtered and the effluent filtrate stream. Typical results were 20 millivolts for a pressure difference of 200 lb. per sq. in. It is obvious that potentials of this order will not explain the potentials of 100 mv. or more that normally are observed in logging wells. When it is realized that only a small fraction of the total electrofiltration potential will be represented by the drop in potential in the drilling mud, the discrepancy becomes even more striking.

In the field experiment, an electrode was placed opposite a sand where a large potential difference was observed. Pressure was placed on the well by means of the mud pumps. A maximum additional pressure of over 500 lb. per sq. in. was applied. This raised the pressure drop from well to reservoir to approximately three times normal and yet the potential changed by only 25 per cent. Thus, even if electrofiltration potential were the only potential that changed with pressure, it would, in this case, have accounted for less than 15 per cent of the total potential observed. Actually, nearly all electrochemical potentials vary with pressure, so that it is likely that less than 10 per cent of the observed potential resulted from the electrofiltration potential. It is then not surprising that the correlation between permeability and natural potential is poor; nor is it too remarkable that a sand sometimes fails to make itself noticeable on the potential log.

Electrochemical Potentials

What causes the other 90 per cent or so of the potential? The orthodox answer[2] is simple. The second cause is said to be another even more familiar and more thoroughly studied phenomenon—electrochemical potentials. Electrochemical potentials resulting from unlike metals in an electrolyte are everyday occurrences—in flashlight batteries, for example. Likewise, it is common knowledge that, when two different electrolytes are in contact, there is a difference in potential across the boundary. The electrolytes need not have different solutes; it is sufficient if the concentrations are different in the two electrolytes. This is the case that is familiar in oil wells where there are fresh-water and salt-water sands differing substantially in

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injection well where there is no filter cake on the face of the sand. Compare also Fig. 9 of this reference.

* Performed by M. Williams, Production Research Department, Humble Oil and Refining Co., Houston, Texas.

concentration. In such a case, the potential is given by a simple formula:

$$E = k \log C_1/C_2 = k(\log C_1 - \log C_2)$$

where E is the potential, k is a constant depending on the nature of the electrolyte and C_1 and C_2 the respective concentrations in the two electrolytes. It will be found that, for salts that commonly occur and for concentration differences that are reasonable, the potential is unlikely to be large enough to account for the potentials measured by the electrical logger. Except for this, it would seem that this is a reasonable explanation, although somewhat less satisfying than electrofiltration, since its connection with sands is less obvious.

Fallacy

Unfortunately, this simple theory has a fatal fallacy. The method used in logging is to move one electrode through the mud, which is considered to be a reasonably homogeneous electrolyte. The electrode does not cross the boundary from one electrolyte into another, so it can be affected by these potentials only indirectly. Ignoring inhomogeneities in the mud, the only way there can be a difference in potential between two points in the mud is for a current to flow in the mud; for, since the mud is a conductor, current will flow between points at different potentials. Thus, the various potential differences across the contacts between electrolytes must cause current to flow in the drilling mud if they are to affect the potential log. From the formula for the potential E due to differences in concentration, it can readily be seen that the sum of such potentials around any path, beginning and ending in the same electrolyte, must be zero. Therefore, these potentials, contrary to the popular theory, have no effect on the log. In many other cases, where the two electrolytes have different solutes, a similar equation holds for the potentials, and it can be shown in a similar fashion that they have no effect on the potential log.

Chain of Electrolytes

It is known that under certain conditions current will flow in a chain of electrolytes. The general conditions are not known. It is obvious, however, that, since energy is dissipated by the flow of current through materials that are not perfect conductors, energy must be supplied by some reaction occurring at or near some of the interfaces. In general, this will lead to a decrease in the potential with time. A lessening of potential has been observed sometimes when the section of a well was rerun after a lapse of considerable time.

While studying this problem, the senior author discovered one condition under which current will flow in a chain of electrolytes. This particular condition is interesting because it is one that exists in wells and because it gives a qualitative and semiquantitative explanation of some apparently abnormal logs. For example, it explains how a zone of low potential may exist in the middle of a sand, which by the conventional interpretation would indicate a tight zone, where actual tests show that the permeability is about the same as in the remainder of the sand.

This investigation was begun because of the suggestion, based on observation of logs made with nonpolarizing electrodes, that the shale zones were the seat of the phenomena largely responsible for the potentials measured in logging wells. A circular trough was divided into three sections by partitions of unglazed porcelain. These sections were then filled with three different electrolytes. Two carefully prepared nonpolarizing electrodes were placed in one of the sections. It was always found in agreement with theory, that when the electrolytes differed only in concentration, the electrodes were at the same potential,

demonstrating that no current was flowing. Similar results were obtained with many combinations of electrolytes. If clean sand cores were used as partitions, only small potentials were observed; but when shale was used for the partitions, quite large potentials were observed. Fig. 1*a* shows a modification of this experiment. One section is filled with shale. Section I is filled with fresh water. Section II is filled with salt water. The two sections are separated by a permeable membrane. Current flows in the direction from section I to section II. If both sections were filled with fresh or both with salt water of equal concentration, no current would flow. If section I were filled with salt water and section II were filled with fresh water, the direction of current flow would be reversed. In Fig. 1*b*, the analogous situation as it exists in a well is

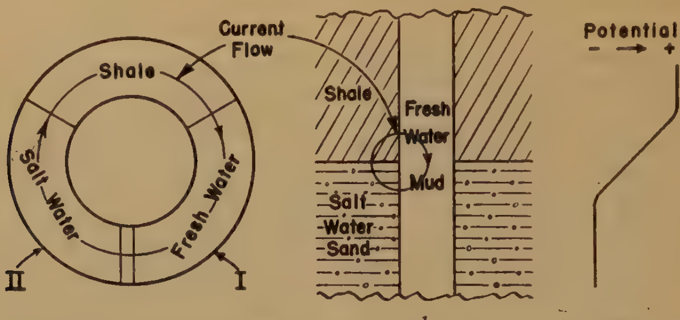

FIG. 1.—EXPERIMENTS WITH COMBINATION OF ELECTROLYTES.

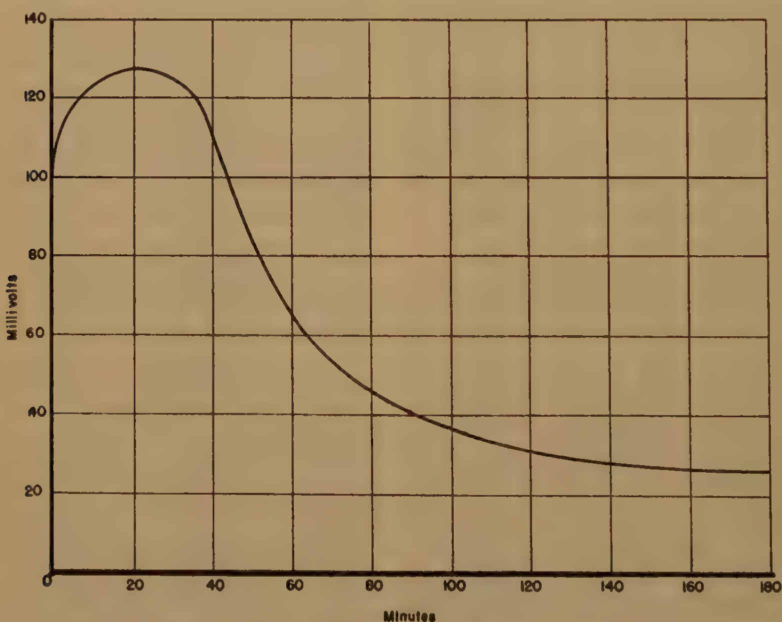

FIG. 2.—RELATION BETWEEN TIME AND ELECTROMOTIVE FORCE.

illustrated. If the water in the sand is more saline than the mud, current will flow from the shale into the drilling mud. Fig. 1*c* illustrates the corresponding potential log. Fig. 1*a* shows that if the mud is more saline than the water in the sand, the direction of current flow will be reversed and as a result the potential log will be reversed. A case has been observed where ordinary tannate mud was replaced by silicate mud after the well had reached a considerable depth and after preliminary electrical logs had been made. In this instance, the potential curve was completely reversed when the hole was filled with silicate mud, giving a mirror image of the normal log. If in Fig. 1*a* the shale section is replaced by clean sand, clean porous limestone, etc., no current will flow.

In order to obtain quantitative data, equipment was built so that the potential difference between a salt-water solution and a fresh-water solution, separated by a core, could be measured with calomel half-cell electrodes. It was found that, when the core was a clean sand, the potential difference was of the order of 5 mv.; whereas, with a shale core, the potential difference was 100 to 150 mv. with the fresh water positive. It was interesting to notice that the potential was not constant. Fig. 2 shows a curve of the relation between time and electromotive force for one such sample.

Fig. 3 shows a comparison of potentials measured for a series of cores with the electrical log made in the well from which the cores were obtained. When it is recalled that there will be some potential drop in the formation, the correspondence is rather striking.

The mechanism of this phenomenon is not clearly understood, but it does appear to shed more light on the true basis of potential logging than do the older theories. This work suggests that when fresh-water drilling mud is used, the potential log may be largely a measure of the absence of argillaceous material in the formation. This conclusion is confirmed by the observation that large "kicks" are often found opposite beds of dense limestone and that most

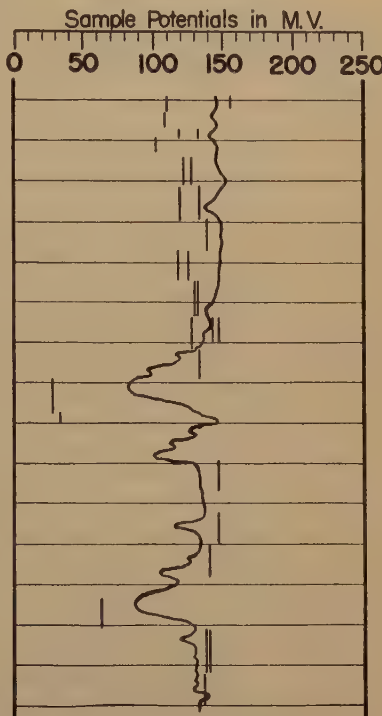

FIG. 3.—COMPARISON OF SAMPLE AND LOG POTENTIALS.

permeable beds that do not show "kicks" are found to contain substantial amounts of shaly materials.

The utility of natural potential logs is enhanced by the fortunate circumstance that in many areas the oil and gas-producing formations are strata consisting largely of sand lying between shale or clay bodies. As a result, kicks like that shown in Fig. 1*c* are obtained at the top and bottom of the producing formation. However, it is not unusual for the sand bodies to contain considerable admixtures of shale finely disseminated in some portions or throughout the sand. In such cases, the log

may suggest the presence of a tight zone, which actually is nonexistent or may fail to give sharp indications of the boundaries.

References

1. J. Zaba: Limitations of Electrical Logging. Drill. and Prod. Practice, 1941. Amer. Petr. Inst.
2. C. A. Heiland: Geophysical Exploration, 831–833.
   J. J. Jakosky: Exploration Geophysics, 679–684.
   L. L. Nettleton: Geophysical Prospecting for Oil, 385–387.
3. D. A. McInnes: Principles of Electrochemistry, chap. 23, 423.
4. W. J. Gillingham: Electrical Logging in the Appalachian Fields. Mineral Industries Expl. Station *Bull.* **21**, (Penn State College 1937) 30–52.
5. R. J. Schilthuis: Connate Water in Oil and Gas Sands. *Trans.* A.I.M.E. (1938) **127**, 199.
6. H. T. Byck: The Effect of Formation Permeability on the Plastering Behavior of Mud Fluids. Drill. and Prod. Practice 1941. Amer. Petr. Inst.

Some Practical Aspects of Radioactivity Well Logging

By Warren J. Jackson,* Member A.I.M.E. and John L. P. Campbell*

(New York Meeting, February 1945)

Abstract

Automatic recording of the radioactivity of the earth's formations provides a log of relative intensities that, if properly interpreted, can be applied to oil-field engineering. Production, engineering, and geological departments regard the radioactivity log as a forward step in the securing of more conclusive information for successful well completions. Explanations of the technique, together with some of the problems to which radioactivity logging have been applied, are presented in this paper.

Introduction

Those responsible for the completion of new oil and gas wells, or with planning workover operations on old wells, have followed closely the development of radioactivity well logging because they are interested in reducing the number of unknowns that usually are present in such work. Many operators have made use of the log, or are acquainted with at least one of the applications, but it is unlikely that any one operator is familiar with all of the many applications that are possible.

The purpose of this paper is to present a representative example of each of the many applications, wherever the information has been released by an operator, and to illustrate by hypothetical examples other applications, releases for which have not been given. In this way, it is hoped that a better understanding of the scope of this new engineering tool may be obtained.

Although the literature contains many references that describe in detail the theory, development, and application of radioactivity well logging, a brief discussion of the technique may be helpful to those who are investigating the subject for the first time.

All rocks contain radioactive material in varying concentrations. In general, shales contain relatively more radioactive material than sandstones or limestones. These radioactive materials disintegrate with time into other materials of lower atomic weight, and in that process of disintegration the rocks are emitting many rays, the most penetrating of which is the gamma ray. The intensity of emission of the gamma ray is proportional to the quantities of radioactive materials present. A higher rate of emission would be observed, therefore, opposite a shale than opposite a sandstone or limestone.

Since measurable intensities of gamma rays are capable of penetrating as many as five concentric strings of casing, and as the gamma-ray intensity is relative to the formations, the measurements of variations in gamma-ray intensities offer a means of identifying cased-off formations in their proper stratigraphic sequence.

The Gamma-ray Curve

The measurement of gamma-ray intensities is accomplished by means of an ionization chamber that consists of a heavy cylinder, about 3 ft. long, that contains two insulated electrodes and is filled with an inert gas under high pressure. Under normal conditions no current will flow through the gas when an electrical potential is set up between the electrodes, but when

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* The Lane-Wells Company, Dallas, Texas.

the chamber is exposed to gamma-ray radiation the gas becomes partly ionized and permits the flow of a very small current between the electrodes. The amount of this current varies directly as the ionization, which, in turn, is proportional to the intensity of the gamma rays acting upon the gas.

An amplifier in the instrument case with the ionization chamber amplifies these small variations in current, and transmits them, through the logging cable of the hoist truck, to the instrument truck. The instrument truck contains additional amplifiers, sensitivity controls, and an automatic pen-type recorder that translate down-the-hole signals into variations in amplitude of a curve that is developed on a strip chart moving in synchronization with the instrument. The curve that records the variation in intensity of the gamma-ray emissions of earth material with depth is called a gamma-ray curve.

Because both sandstones and limestones are recorded as minimum values on the gamma-ray curve, it is almost impossible to distinguish between the two by inspection of the curve alone. To enable positive identification of sandstone and limestone, the neutron curve was developed to complement the gamma-ray curve.

The Neutron Curve

The neutron curve is obtained through the use of an instrument identical to that previously described, but with the addition of a neutron source appropriately shielded from the ionization chamber. Neutrons from this source bombard the earth material immediately surrounding the well bore, and the effect of this bombardment is measured by the ionization chamber. The character of the recorded measurement is such that if the formation contains hydrogen, which is commonly associated with well fluids, the intensity of the recorded curve is considerably less than if the formation were dense and devoid of fluid.

Thus, when a minimum value on the gamma-ray curve is interpreted as either sandstone or limestone, a minimum value on the neutron curve would indicate sandstone, and a maximum value would indicate a dense limestone. This responsiveness of the neutron curve to the presence of fluid also makes it possible to identify zones of porosity in limestone or chalk sections. It should be explained that, although the neutron curve is responsive to well fluids, it cannot distinguish between them, and therefore cannot be used to determine the type of fluid in a subsurface rock.

Bottom-water Shutoff

Fig. 1 illustrates a typical "bottom-water" plug-back operation in the Conroe field, Montgomery County, Texas. The original completion was based on coring information, and the casing was set above the producing stratum, with a liner set through the pay zone. Water production had increased to 30 per cent when plugging back operations began.

A gamma-ray log was run to select a more favorable zone, and the results are shown in Fig. 1. The casing seat is indicated clearly on the log by a shift to the left. The top of the liner also is shown by contrast, in the dampening effect of two strings, versus one string, of pipe, indicated by a shift to the right at the point where only one string of pipe was set.

The liner was perforated opposite the shale at a depth of 5058 to 5064 ft., and a satisfactory squeeze job was obtained, following which the well was perforated for production from 5043 to 5048 feet.

On a production test the well flowed at a daily rate of 100.06 bbl. of pipe-line oil on ⅛-in. choke, with a tubing pressure of 500 lb. and a gas-oil ratio of 538 cu. ft. per barrel.

Plugging Back to Upper Pay

Before the introduction of electric logging, a log of a well usually consisted of a

composite record constructed from cores, cuttings, and the driller's interpretation of the formations. The accuracy of such a log was affected by lost cores, careless sampling and measurements, and frequently by weather conditions. Fig. 2 illustrates such a log. This well recently became depleted to a point where abandonment or recompletion had to be considered. From an analysis of the condition of the well it appeared advisable to run a gamma-ray log because subsequent wells had cored, and logged, a gas sand that was not reported on the log of this well. Because gas was needed for local operations, the gamma-ray log was run upward from 6150 to 5000 ft. with a permanent zero point at the lower Christmas-tree flange. The core record, corrected to the same measurements of the lower Christmas-tree flange, showed good correlation agreement. The gamma-ray curve logged a sandstone stratum at a depth of 6050 ft., a point at which no cores were reported.

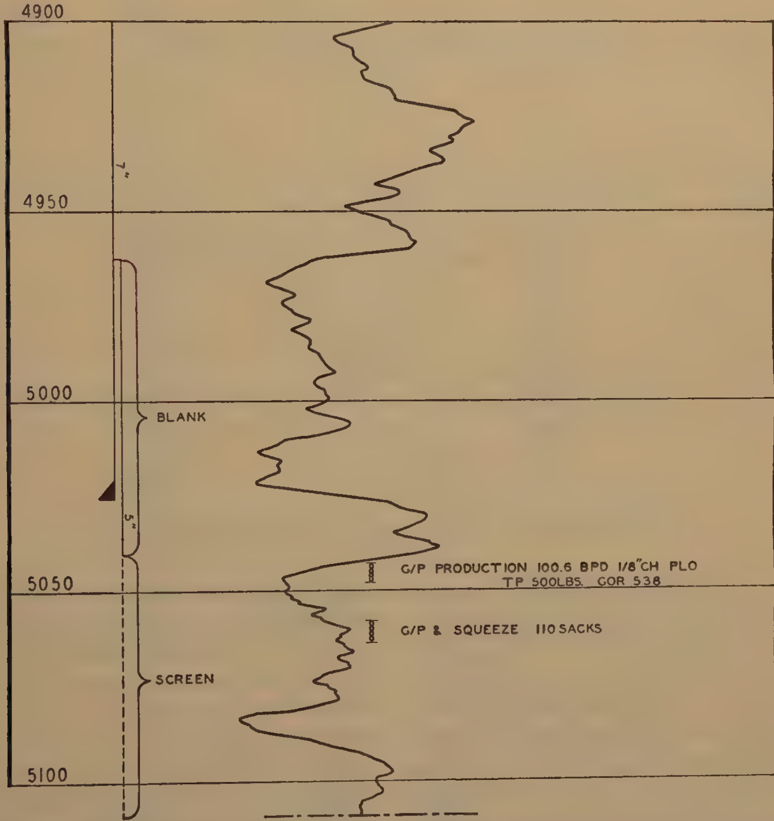


Fig. 1.—Typical application of gamma-ray log in bottom-water shutoff, Conroe Field, Texas.

It should be noted, also, that although the zone from 6035 to 6068 was cored, the reported recovery of only the bottom 2 ft. was actually below the stratum found by the gamma-ray log. The sandstones and shale of the section are so unconsolidated that the cores probably were washed out before reaching the surface.

The well was completed in 1935, and since that time it has been produced from

the gun perforations shown on the graph to the right of the core record. With the gamma-ray log information at hand, the operator squeezed off the old perforations with 100 sacks of cement under a pressure of 2500 lb. per sq. in., and set a packer at 6000 ft.—11 ft. above the uppermost perforations. Fifty-eight sacks of cement was forced into the formations, 28 sacks was left inside the 7-in. casing, and 14 sacks was washed out through the 2½-in. tubing. The top of the cement plug was at 6073 ft., and with this as a new bottom, the 7-in. casing was gun-perforated with 27 holes from 6050 to 6065 ft. After a test to determine the potential, the well was completed as a gas well, with sufficient volume to satisfy the local needs.

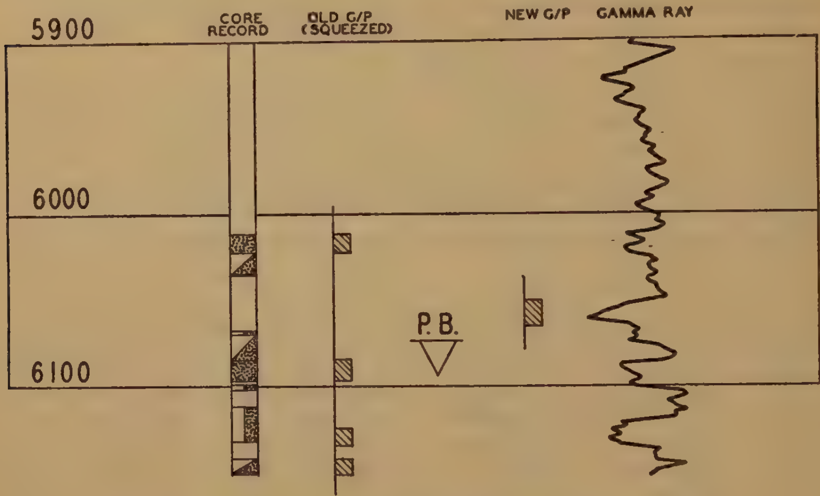


FIG. 2.—GAMMA-RAY LOG APPLIED IN PLUG-BACK TO UPPER PAY.

SALT-WATER DISPOSAL

Fig. 3 illustrates a driller's log and a gamma-ray log of a well drilled and completed by cable tools in February 1920 in the Electra field, Wilbarger County, Texas. The initial daily production was 30 bbl. from a depth of 1905 to 1930 ft., which is the main pay sand of the field.

Because of salt-water encroachment, the operators discontinued the well on production and converted it to an injection well for the disposal of salt water in the upper nonproductive zones. A gamma-ray log was run for the purpose of verifying the stratigraphy of the driller's log, and to determine the exact depth and thicknesses of any cased-off sandstone or limestone formations that could be used for the disposal of salt water.

After the log had been run, the well was plugged back, in February 1944, to 1802 ft., where the 7-in. casing was set originally. The well then was gun-perforated with 75 holes in the zone designated *A*, between 1340 to 1365 ft., and with 39 holes in the zone designated *B*, between 1483 to 1498 ft. In May 1945 a total of 150 bbl. of salt water per day was being pumped into these two beds at a pressure of 400 lb. per sq. inch.

While the purpose of the gamma-ray log was to verify the stratigraphy, a comparison of the two logs revealed that zones *A* and *B* were not indicated on the original driller's log. The absence also of the other sandstone or limestone formations as disclosed by the gamma-ray log is apparent

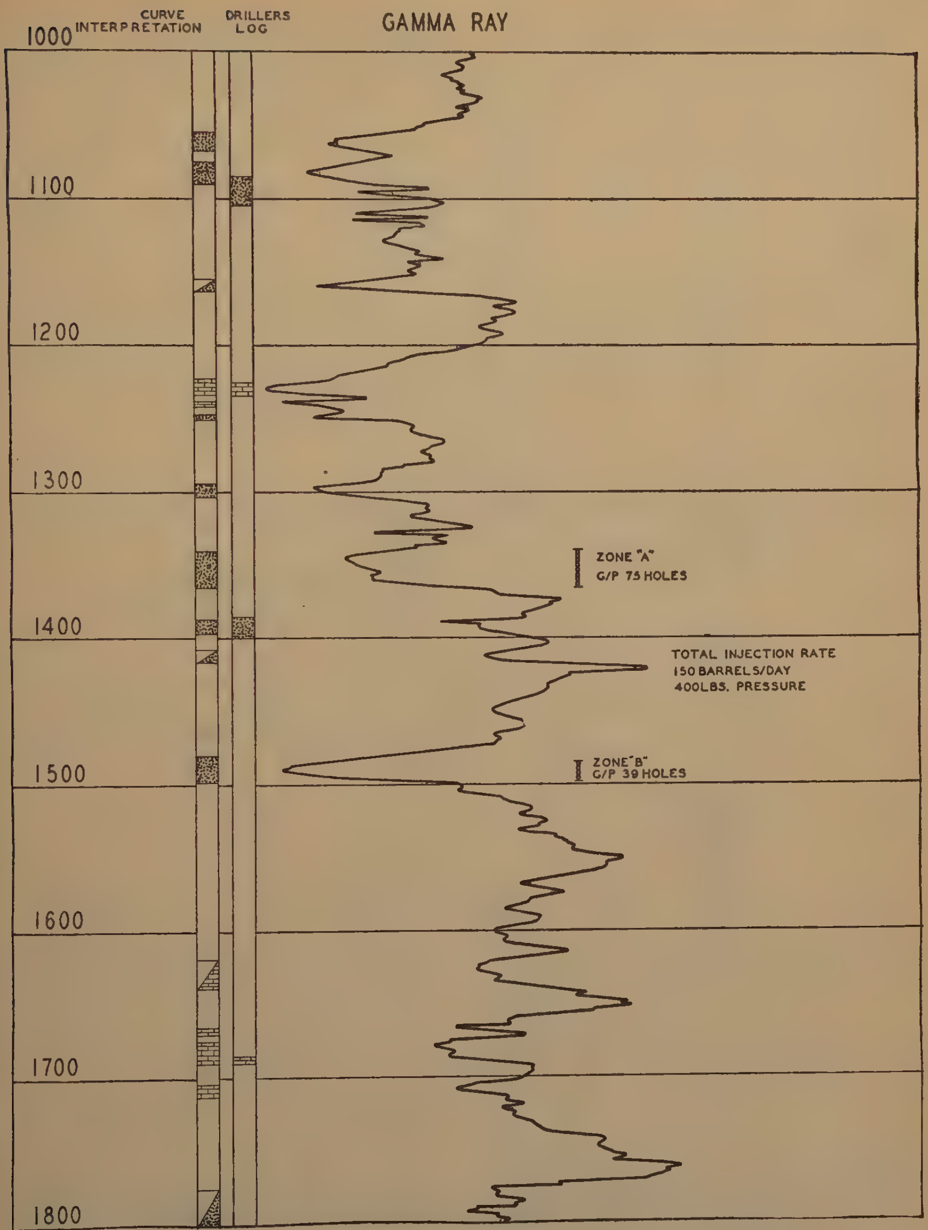


FIG. 3.—GAMMA-RAY LOG APPLIED IN LOCATION OF SALT-WATER DISPOSAL SANDS.

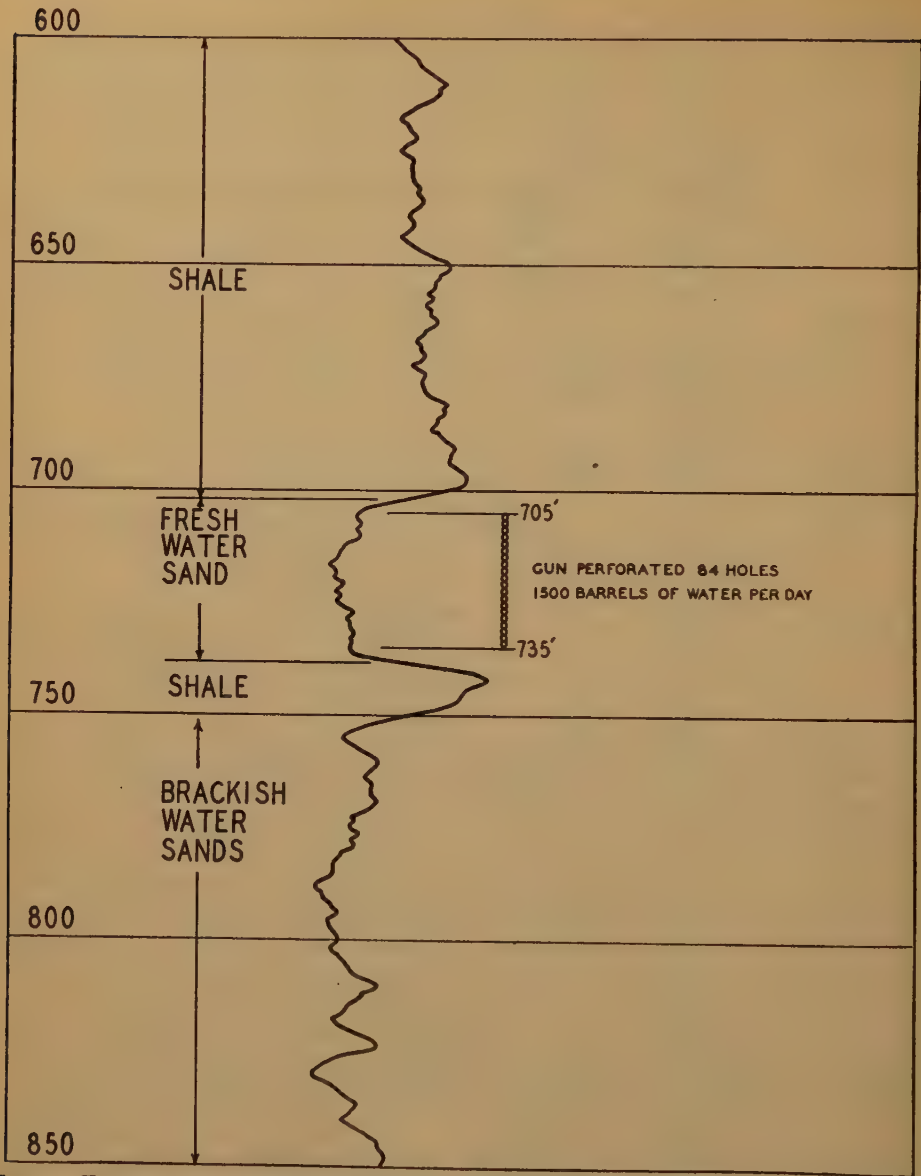


FIG. 4.—TYPICAL APPLICATION OF GAMMA-RAY LOG IN LOCATION OF POTENTIAL FRESH-WATER SANDS, DRISCOLL FIELD, TEXAS.

from the upper section of the log. The disagreement regarding the tops and thicknesses of the zones will be noted in the sections of the two logs that are in partial agreement as to the lithology of the zones.

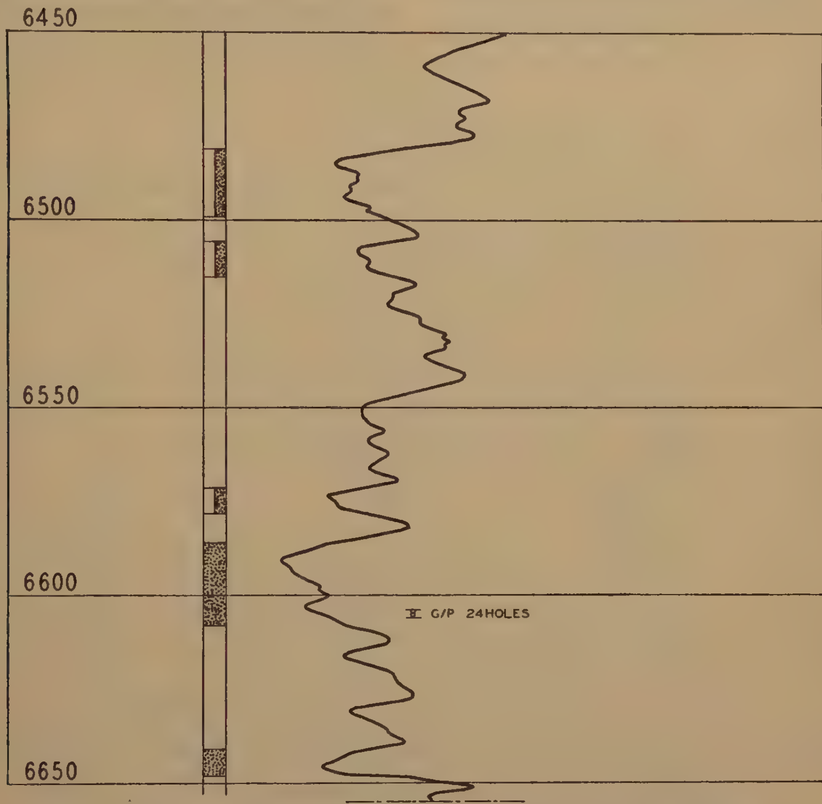


FIG. 5.—GAMMA-RAY LOG APPLIED TO LOW-GAS-OIL-RATIO RECOMPLETION.

FRESH-WATER SUPPLY

Many depleted wells, or dry holes, could be utilized for fresh-water supply instead of abandoning and terminating their period of usefulness.

Fig. 4 illustrates how a dry hole in the Clara Driscoll field, Nueces County, Texas, was used to supply fresh water for a ranch on which the former supply had failed, and incidentally, to supply water for a number of near-by drilling operations.

The gamma-ray log was run to locate a sandstone stratum behind the cemented 10¾-in. surface pipe, which was known to be at some depth below 700 ft. The fresh-water-bearing sandstone was found between 702 and 739 ft., and the casing was gun-perforated from 705 to 735 ft., with 84 holes of 15⁄32-in. diameter.

Water rose to within 10 ft. of the surface, and the well was equipped with a windmill and electric pumps on separate strings of tubing. Production of as much as 1500 bbl. of fresh water per day has been reported, with no appreciable reduction in hydrostatic head.

As a result of this work, another rancher, who was in desperate need of water, ordered a gamma-ray log of an abandoned well that was downdip from the well shown in Fig. 4. The same sandstone stratum occurred at a depth of 750 ft., and after the

top 25 ft. of the bed had been perforated the well produced at a comparable rate.

Lowered Gas-oil Ratio

The Webb sand in the Flour Bluff field was cored continuously, and the cores indicated a gas-bearing stratum. Production data showed that the reservoir had an expanding gas cap. The depletion to non-commercial quantities of oil from the Phillips sand had caused some operators to plug back their wells to the Webb sand, and to test the extreme bottom of the sand. By selectively gun-perforating a precise interval, commercial quantities of crude oil were produced from an indicated gas-bearing stratum. The change of an expanding gas cap to contracting gas cap was caused by water encroachment, which in its movement has cleansed the sand by pushing the oil upward. Only the edge wells on the steeply dipping flanks, however, produce oil.

The operators in this field were faced with the problem of precise recompletion after plug back, and in order to eliminate any doubt, gamma-ray logs were obtained to locate, accurately, the relative positions of the sand and the bottoms of wells after plugging back. Following the survey, the casing was gun-perforated for squeeze-cementing from 6598 to 6600 ft., to separate the gas and oil, and later the bottom 2 ft. was perforated with 24 holes from 6604 to 6606 ft. The results were most encouraging. The well produced at the rate of 108 bbl. of pipe-line oil on ⅛-in. choke, with a gas-oil ratio of 1450 cu. ft. per barrel. The gamma-ray log is playing a vital role in this field, where low ratios are of prime importance.

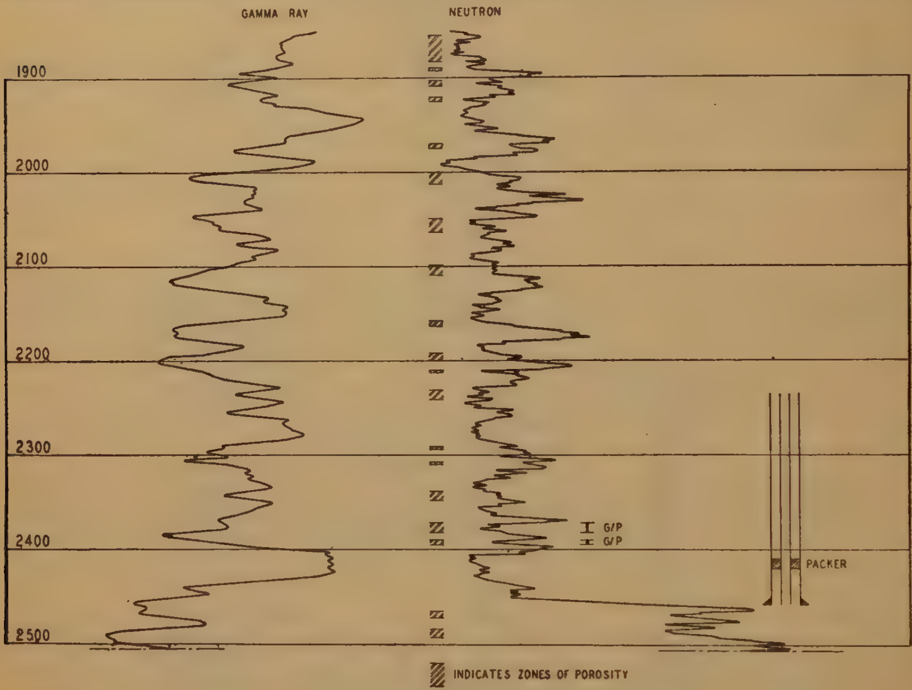


Fig. 6.—Combination radioactivity log indicating zones of porosity.

Locating Zones of Porosity

As mentioned earlier, zones of porosity can be identified by combining the gamma-ray and neutron logs. It will be recalled

that a dense limestone normally will be recorded as a minimum relative value on the gamma-ray log whereas on the neutron log it will be reflected as a maxi-

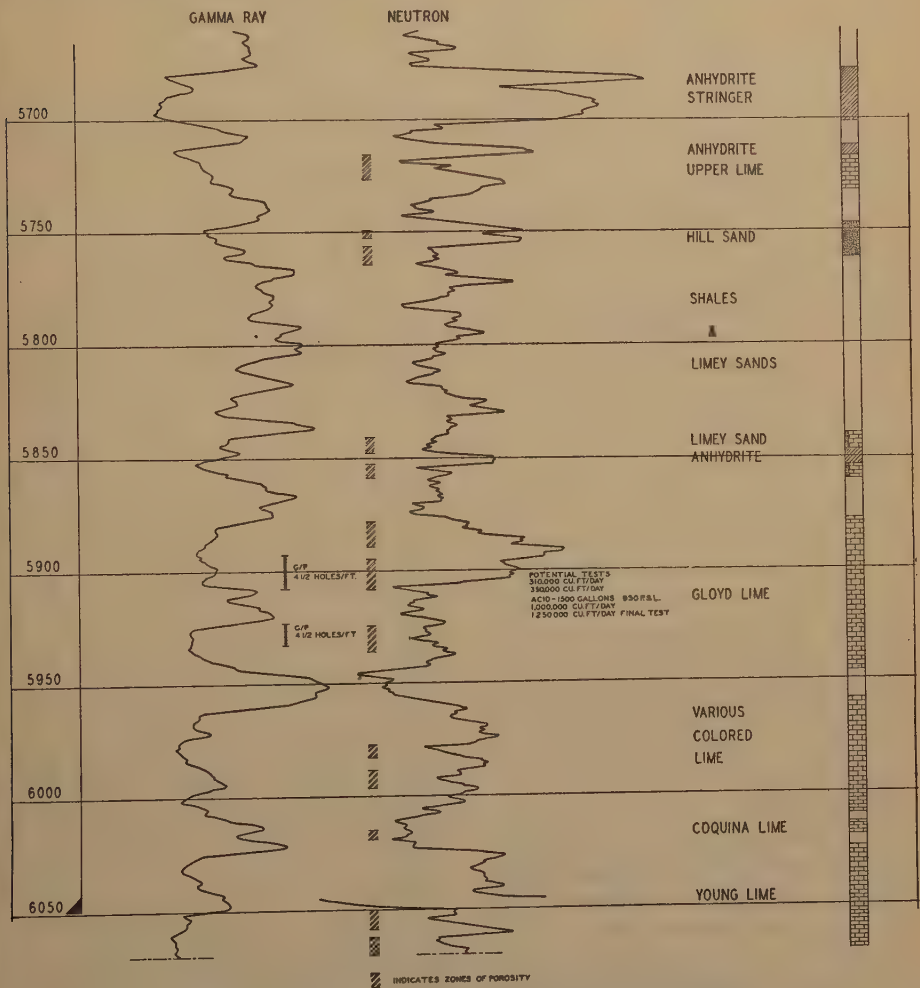


FIG. 7.—TYPICAL COMBINATION RADIOACTIVITY LOG IN THE RODESSA FIELD.

mum relative value, because of the absence of formation fluids. Any zone of porosity in a limestone normally will be indicated by a shift to the left of the neutron curve, because of the effect of the hydrogen associated with formation fluids occupying the pore spaces.

For Oil Production

Fig. 6 illustrates the manner in which the foregoing response patterns were used to complete a well in the Wimberly pool, Jones County, Texas, in which the hole was drilled through the Hope limestone, and the casing was set on top of the Gunsight limestone. No electrical log was run, and no cores were taken.

Gamma-ray and neutron logs were obtained after the casing was set, and the

hole was deepened to the bottom pay at a total depth of 2509 ft. The sharp break on the neutron curve shows the casing seat to be 2458 ft., which compares with 2460 ft.

FIG. 8.—RADIOACTIVITY PERMEABILITY STUDY.

shown on the casing record. The varied character of the formations is shown clearly by the radioactivity log. Zones of porosity within the limestones are indicated by the crosshatched blocks in the column between the two curves.

From these indications the zones from 2372 to 2387 ft., and from 2390 to 2395 ft. in the Hope limestone were gun-perforated. The porous streaks in this stratum, together with the lower open-hole section, were treated with 1000 gal. of acid. A dual completion was made by setting a packer and side-door choke assembly between the two limestone zones. On potential test, the upper zone flowed at the rate of 80 bbl. per hour through 2-in. diameter flow line, and the lower zone flowed at the rate of 65 bbl. per hour through a 2-in. diameter flow line. The allowables for both strata are 60 bbl. per day.

FOR GAS PRODUCTION

Another illustration of the application of the two curves in the location of porous zones within limestone sections, and the production of gas known to exist in the sections, is given in FIG. 7. This combination log of a well in the Rodessa field, Louisiana, indicates the porous streaks in the Gloyd lime. The combination radioactivity survey indicates the utility of the tool in fault-line producing fields, where the porosity in the main pay zones is spotted.

The Rodessa field has little information that is correlative from well to well, and the economy in workover operations is paramount. Rather than gun-perforate from correlative core records, the owner of this well preferred to run the survey for a record, and gun-perforate selectively. As the former pay zone was in open hole, it was desirable to log its porosity, and also accurately locate the casing seat, which can be accomplished easily with the neutron log. The 7-in. casing was found at a

depth of 6049 ft., where a sharp shift to the left was observed on the neutron curve. Clear definition of all the formations is depicted by the gamma-ray curve and of the porous zones by the neutron curve, which are indicated on the chart by the crosshatched blocks. To eliminate bottom-hole water adequately, a wire-line bridging plug was set at a depth of 5975 ft., and three sacks of cement was dumped on top.

The Gloyd limestone was selectively gun-perforated according to the neutron indications from 5893 to 5908 ft., and from 5923 to 5932 ft. The production test showed an immediate flow of 310,000 cu. ft. of gas per day, which gradually increased to 350,000 cu. ft. per day.

After acidizing through the gun perforations with 1500 gal. of acid at a maximum pressure of 930 lb. per sq. in., the well increased in flow to 1,000,000 cu. ft. per day, and finally was completed with a test of 1,250,000 cu. ft. per day. When that production declines to a point where further workover is necessary, the additional zones of porosity indicated on the log may be tested, to extend further the life of the well before abandonment.

Permeability Studies

Work of an experimental nature is being done with regard to the application of radioactivity logging to obtain what properly may be termed a "relative permeability profile" in limestone producing horizons.

The specific need for such information was suggested by engineering studies in various limestone producing fields for the selective completion of wells to inject gas or water into the producing horizons for secondary-recovery operation.

The procedure consists, essentially, of running a gamma-ray log to provide a lithologic log of the well, and the neutron curve to locate possible fluid-bearing zones. This is followed by pumping a radioactive tracer, mixed with salt water or oil under pressure, into the producing horizon. By successive runs of the gamma-ray curve the distribution of the radioactive fluid into the permeable zones is indicated on the log.

Because the work to date has not been released for publication, a hypothetical illustration is shown in Fig. 8. It will be noted on the log that the intrusion of the radioactive fluids into the most permeable zone is indicated by successive gamma-ray surveys, which complement the neutron log for proper interpretation of porosity and relative permeability.

A convenient radioactive tracer may be obtained by a laboratory process from a bromide of the element radium. This substance may be converted to a salt or soap solution, which is completely miscible with the liquid in a well.

Conceivably, in any one area where radioactive tracers are used, the natural radioactive strength of the subsurface formations may be altered and thus destroy the basic data upon which radioactivity surveys are made. Consideration should be given to the use of radioactive tracers having a relatively short life period, so that the effect of the tracer will disappear in a definite time. Many suitable substances possessing desirable properties are unavailable at present.

It is reasonably assumed that the main purpose of a tracer is not only to study the permeability of one well, which in itself would be significant, but rather to study a series of wells on strike, to determine whether permeability is continuous vertically and horizontally.

The practical application of radioactivity logging in such situations will be determined best from the results of further experimental investigation over a wider range of conditions. It is hoped that it will be a means of supplying pertinent subsurface well data in fields where insufficient information relative to the producing horizons is available not only for intelligent

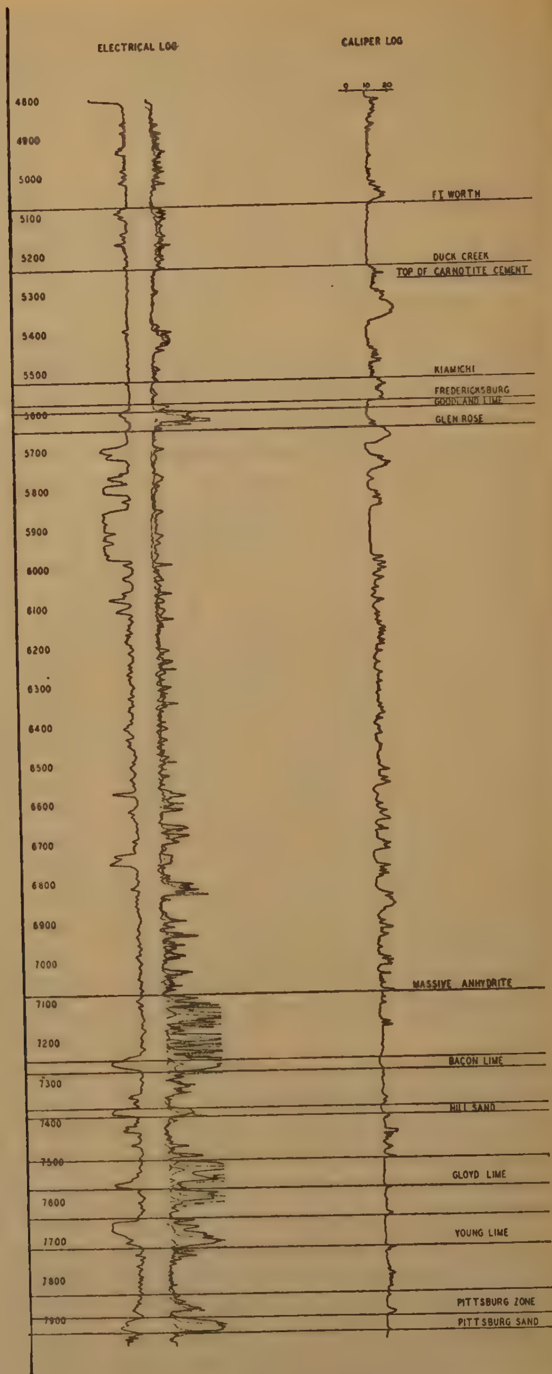
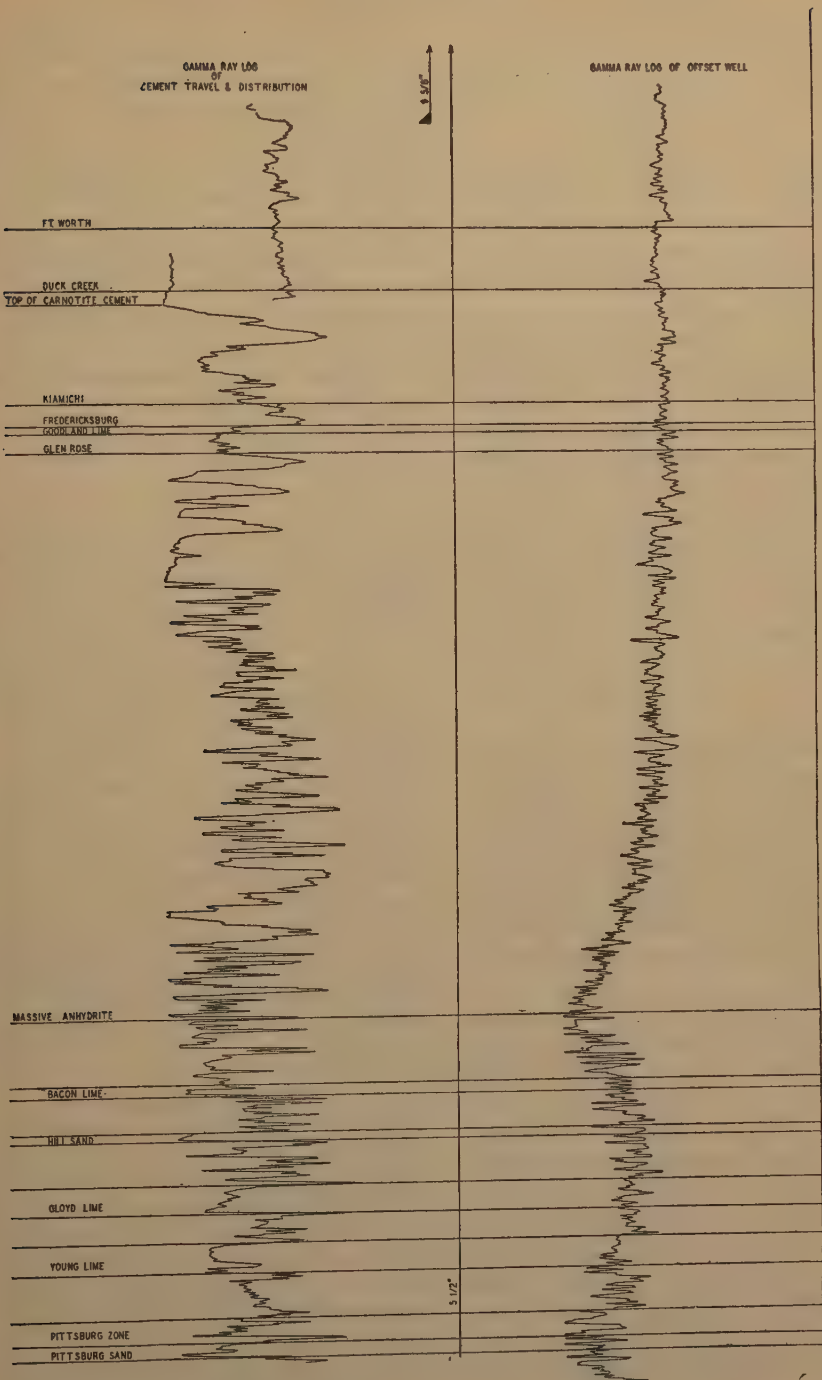


FIG. 9.—GAMMA-RAY ILLUSTRATION



OF ORIGINAL OIL-STRING CEMENTING.

planning of secondary-recovery projects but also for primary-production operations.

Determination of Cement Placement

Original Casing

Frequently, during the development of a field, or in the completion of a particular well, it is important to determine accurately the actual cement fill-up behind the oil string to compare with the conventional methods now employed.

The vertical travel of the cement, as well as an indication of mass distribution, can be obtained by the use of powdered carnotite mixed with the cement. Carnotite is highly radioactive because of its uranium and potassium constituents, and consequently is an ideal tracer. By proportioning the mixture so that the intensity of the gamma-ray response is considerably greater than that usually obtained from the formation alone, it is easy to distinguish the presence of the cement by comparison with natural formation radioactive intensity.

A mixture containing ¼ to ½ lb. of carnotite per sack of cement appears to be a satisfactory proportion over a wide range of conditions. The packaged carnotite is introduced at the mixing hopper, and because of its nearly colloidal texture and specific gravity, it remains in fairly stable mixture with the cement slurry without settling out.

Fig. 9 illustrates a typical investigation of this nature conducted in the New Hope field, Franklin County, Texas. The various steps in the study are shown in sequence from left to right. An electrical log to obtain data on the formations and contained fluids was run. An open-hole caliper survey then was made to determine the variations in the hole diameter. This survey indicated an average diameter of hole of 11 in., which was drilled with an 8¾-in. bit; the enlargement was caused by considerable sloughing of shales and unconsolidated sands.

From the data obtained from the caliper survey it was determined that 1200 sacks of cement would be required to protect all possible productive horizons for testing. The 5½-in., 17-lb. casing was landed at a depth of 7929 ft., and was cemented with 1160 sacks of cement, mixed with ¼ lb. of carnotite per sack. Thirteen sacks was left in the casing, 1147 sacks being displaced behind the pipe.

After normal setting time had elapsed, the cement was drilled out to the bottom of the casing and a gamma-ray survey was made. The sharp reduction in intensity at 5262 ft. indicates the upper limit of the carnotite-laden cement.

Although it is possible to record the natural formation radioactivity as the pipe is suspended prior to cement, the risk of sticking the casing is too great. In many fields, the danger of losing instruments by cave-ins is too great to make a base log in open hole, but an alternative is to log an offset well. Such a method was used in this instance, and is shown on the extreme right of Fig. 9.

The illustration shows that the cement protects all the important zones except those immediately below the surface pipe, which can be squeezed later if deemed necessary. In addition, the gamma-ray log correlates extremely well with the caliper and electric logs in revealing that the bulk of the cement was opposite shales, which normally wash out to a greater degree than the sands.

Squeeze Cementing

Because the conditions attending the cementing of the oil string permit a fairly close estimate of the travel of the cement, the same is not true of squeeze cementing. For many wells it is of considerable importance to have an accurate knowledge concerning the final location of cement squeezed behind the pipe after the original cementing. Because of the various constrictions and the pressures required, it is

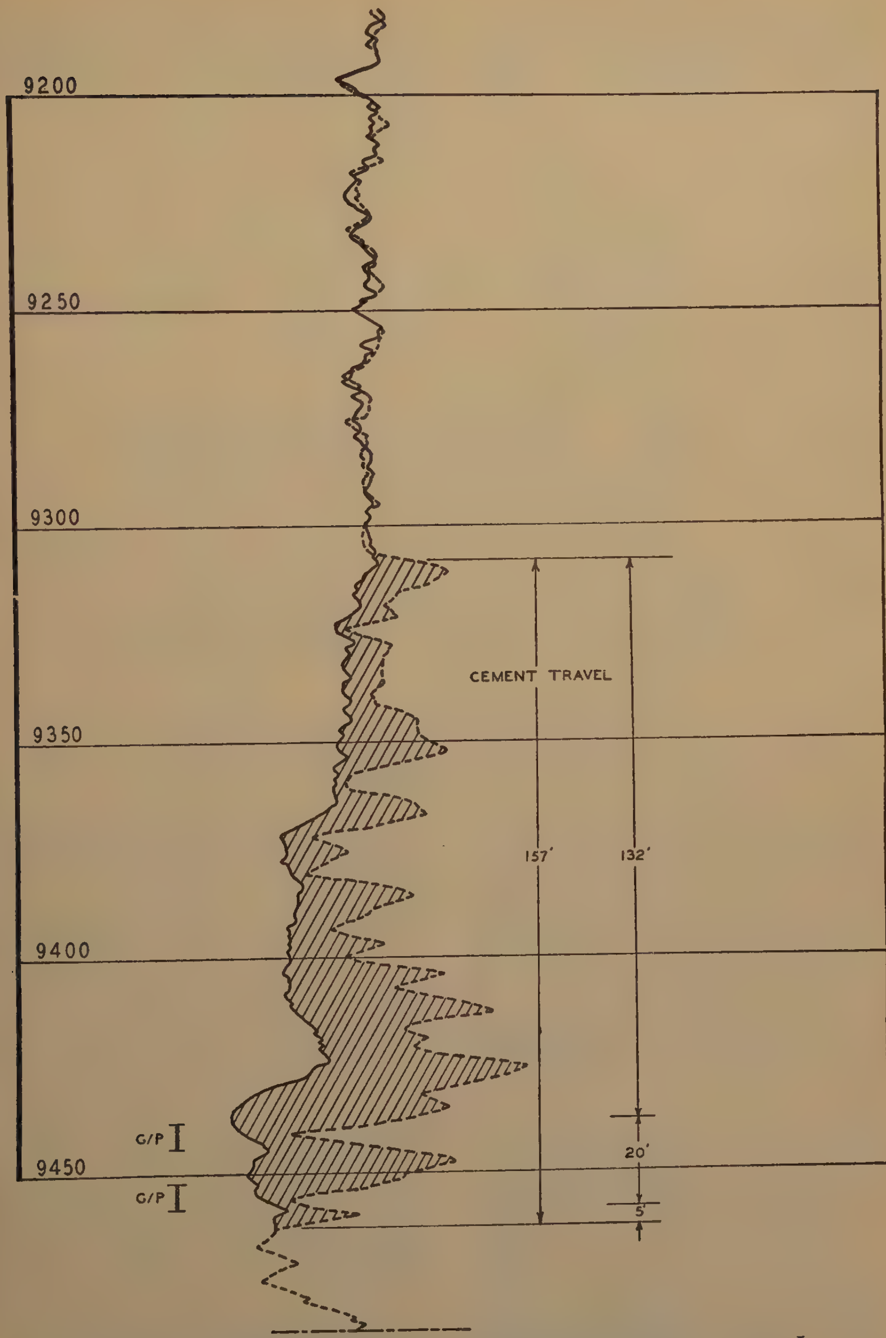


FIG. 10.—TYPICAL SQUEEZE CEMENTING, WITH CARNOTITE SQUEEZE, SOUTHERN LOUISIANA. Solid line, first run; broken line, second run.

impossible to predict how much cement can be squeezed, and whether the bulk of the cement will go up or down, or what effect the lateral distribution as a result of compaction and wedging will have on the vertical limits.

Fig. 10 illustrates typical carnotite squeeze cementing on a well in southern Louisiana. The well was prepared for the squeeze by setting a drillable bridging plug on a wire line at a depth of 9462 ft. and gun-perforating from 9438 to 9444 ft., and 9452 to 9458 ft., with six holes in each zone. The base survey shown by the solid-line curve representing the gamma-ray intensities of the natural formation then was run.

The well was squeezed through the two sets of perforations with 165 sacks of cement, mixed with ¼ lb. of carnotite per sack of cement at pressures ranging from 2000 to 5000 lb. per sq. in. After a 48-hr. set the remaining cement and the drillable plug were drilled out, and circulation was begun to free the inside of the casing of any remaining treated cement.

A second gamma-ray survey was run to a point some 26 ft. below the depth of the first one as indicated by the dashed line. By superimposing the second curve on the first gamma-ray curve, the difference in gamma-ray intensities caused by the presence of the radioactive cement behind the pipe is apparent. When emphasized by crosshatching, this difference is clearly discernible.

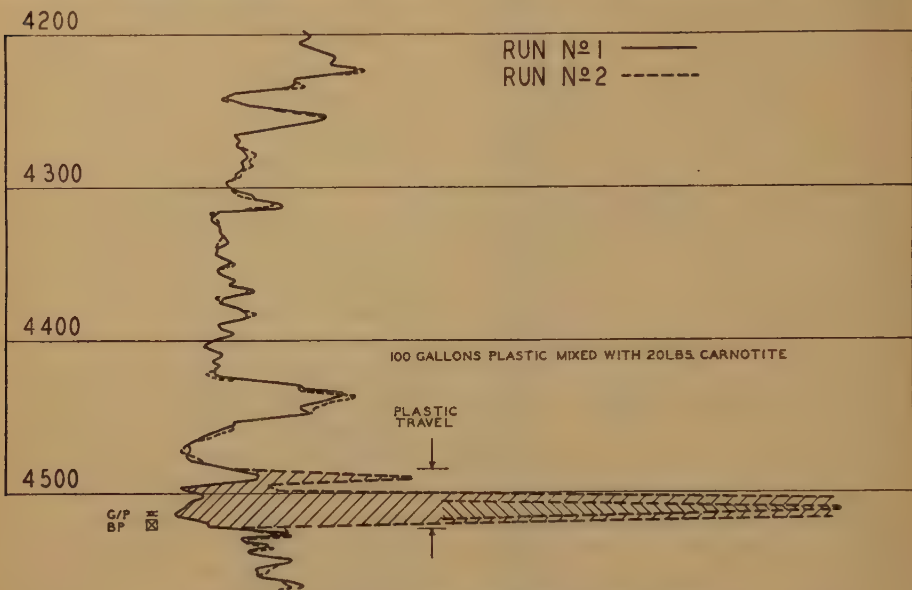


Fig. 11.—Typical plastic squeeze, East Texas.

In this instance the cemented section extends over 157 ft., with the top 132 ft. above the upper perforation, and some 5 ft. below the lower perforation. In other studies of this type it has been noted that the downward travel of the squeezed cement may be as much as one third of the total vertical displacement.

Some conception of the volumetric distribution can be obtained from Fig. 10 by the disclosure that the greater the mass of the treated cement at any point, the greater will be the gamma-ray intensity.

Plastic Squeeze

The properties of commercially available plastics, particularly those that pene-

trate interstitial spaces, enable their use to good advantage in replacing cement under certain critical conditions. Various applications of plastics are understood generally, but it is not so generally known that carnotite can be retained in suspension by plastics while in the fluid state, thus making it possible to conduct investigations similar to those described for carnotite mixed with cement.

Fig. 11 illustrates the displacement obtained on a plastic squeeze applied experimentally on a well in the East Texas area, in an effort to correct an unsatisfactory gas-oil ratio.

Following the standard procedure, a gamma-ray survey first was run to establish the gamma-ray intensities of the natural formation. This curve is shown by a solid line on the figure. The sand of interest is identified by minimum gamma-ray intensity values between 4495 and 5025 ft.

A wire-line drillable bridging plug was set at 4518 ft., and the well was squeezed with 100 gal. of plastic mixed with 20 lb. of finely ground carnotite, through the old perforations at 4514 and 4516 ft. with a pressure of 1300 lb. that built up to a maximum of 1700 pounds.

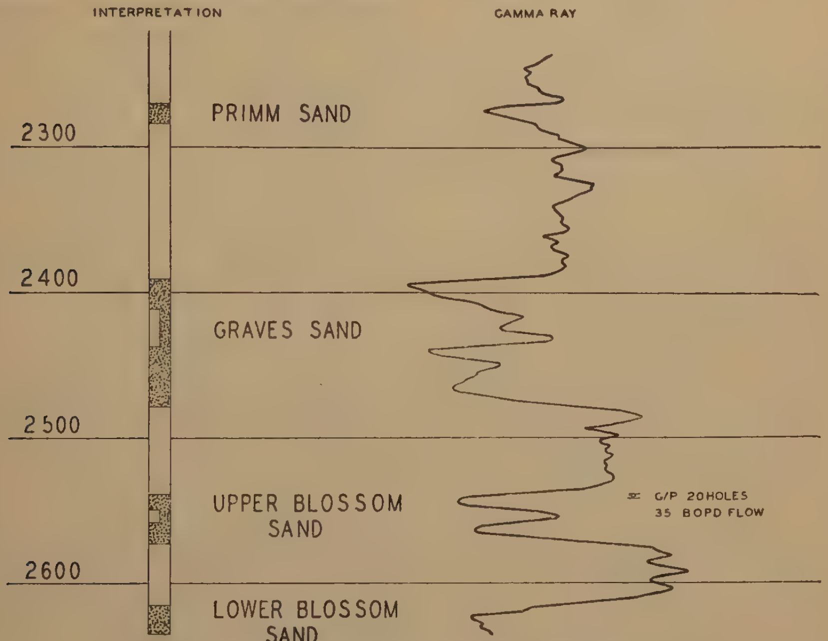


FIG. 12.—GAMMA-RAY EXPLORATION FOR CASED-OFF SANDS.

After a sufficient interval of time had elapsed to permit the hardening of the plastic, the plug was drilled, and the hole was conditioned for the second gamma-ray survey, the curve for which is shown on Fig. 11 as a dashed line superimposed on the first curve. Again the crosshatched area represents the limits of vertical travel and the relative mass distribution of the tracer-laden squeeze material.

The extreme intensity obtained on the second survey is not the result of massive accumulation of the plastic behind the casing, or extreme penetration into the sand, but of the high concentration of carnotite used. Expressed in terms of pounds per cubic feet of cement, the concentration is roughly equivalent to 1.5 to 1, or approximately six times as much carnotite as was employed in cement studies in

which ¼ lb. of carnotite per sack of cement was used.

Gamma-ray Illustration for Exploration

Scores of wells, usually old wells thought to be depleted of all possible oil and gas production, are abandoned annually. Most of these wells were drilled years ago, prior to present-day scientific technology, and no records, other than incomplete driller's logs, are available.

Many of the wells are abandoned because they have a single pay horizon, but in multiple sands or pay zones it is economically important from the viewpoints of ultimate production, or geophysical correlation, to survey the boreholes. Through geophysical correlation and exploitation, oil wells have been surveyed before abandonment, to obtain information that may be helpful when possible field extensions are considered. Fig. 12 is an example of a survey of a well prior to abandonment in order to test any possible cased-off pay zones.

It is a typical example in the Smackover field, Arkansas, but it is applicable to wells in any area. Many of the producing zones at Smackover are blanket sands, but the Upper Blossom sand is lenticular, and it "shales out" from one location to another. During the development of this field most tests were terminated in the Lower Blossom sand, and shallower zones were disregarded. Subsequent stripper tests and exploratory workovers prompted the survey of depleted wells before abandonment, and excellent production has been reported.

Fig. 12 typifies a gamma-ray exploration for cased-off sands. To eliminate doubt and provide a record, this survey was run to determine the presence of upper beds. A sand was recorded at the Upper Blossom level from 2538 to 2572 ft., with an intermediate sandy-shale break from 2548 to 2558 ft. After plugging back with cement, the casing was gun-perforated with 20 holes in the top of the upper stringer from 2538 to 2541 ft. The well came in flowing 35 bbl. of oil per day, and enough gas to operate three additional wells on the same lease, which reduced the lifting cost of all four wells. Forty-four months later the well was producing 8 bbl. of oil per day, and was providing enough gas to operate the three additional wells.

When this sand is no longer considered a commercial producer of oil, the operator plans to drill out the plug to the Lower Blossom sand, and to attempt to recover more oil from this section by using the gas from the Upper Blossom sand.

Structural Correlation on Shale

The natural practice of correlating electrical logs on sandstones or limestones is quite similar to the correlation of several gamma-ray curves, because the gamma-ray curve often is quite similar to the natural potential curve of the electrical log. With gamma-ray logs, however, the correlation on shales is dissimilar. This phenomenal difference is accounted for by the fact that shales vary considerably in their radioactive intensities. The chemical constituents of shales, and their type deposits, make characteristic values apparent on the resultant curve. The correlation on shales in Fig. 13 becomes more significant when it is realized that sands could be correlated as with electrical logs, but precision in the location of the fault plane would not be possible. It is also possible that only one fault plane would be assumed rather than the fault block itself. This precise work was made possible through correlation of shales, which, because of different depositional characteristics, vary in gamma-ray intensity. Bentonites, volcanic ash, and marine shales are characterized particularly by high radioactive values, and they have very distinctive characteristics on a gamma-ray log. In Fig. 13, the two marine shales of each well have been clarified by the heavier lines, and through proper cor-

relation they show the traces of the two apparent fault planes of the block. It is reasonable to assume that with the block field, and they are a great aid in badly faulted fields where the radioactive intensities of shale values are correlatable.

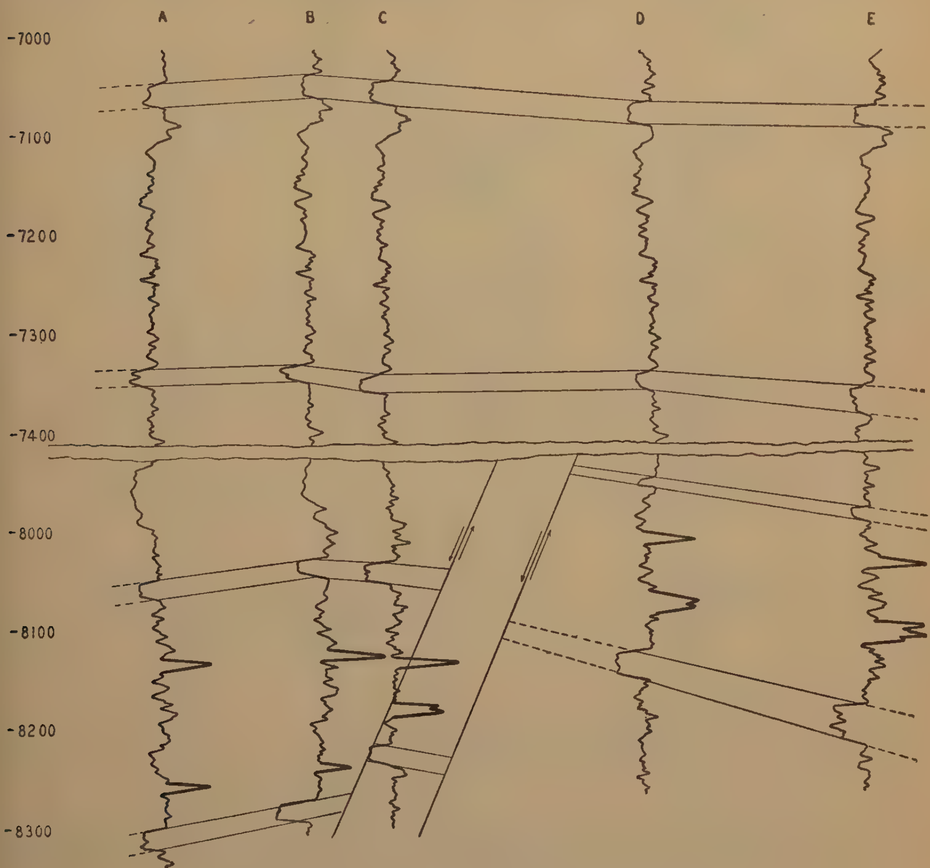


FIG. 13.—STRUCTURAL CORRELATION ON SHALE.

lying between wells C and D, another test drilled between them would find the 8040-ft. sand higher in the fault block, and possibly another productive zone. The normal dip is interrupted by shale correlation as it locates a fault through well C, which, however is not present in offsetting well B. The other fault is known to be present between C and D by correlation of the radioactive shales, and is confirmed by the obvious correlation on sands.

Structural maps can be made with assurance from gamma-ray logs in any

EMERGENCY LOGGING

Under this heading should be grouped the wells in which physical conditions within are such that competent electrical logs cannot be secured normally, but in which a radioactivity log can be obtained to give much of the needed information.

SALT-WATER MUDS

The difficulty of obtaining electrical curves with sufficient character and definition to be significant in salty muds is well recognized. Under such conditions it is

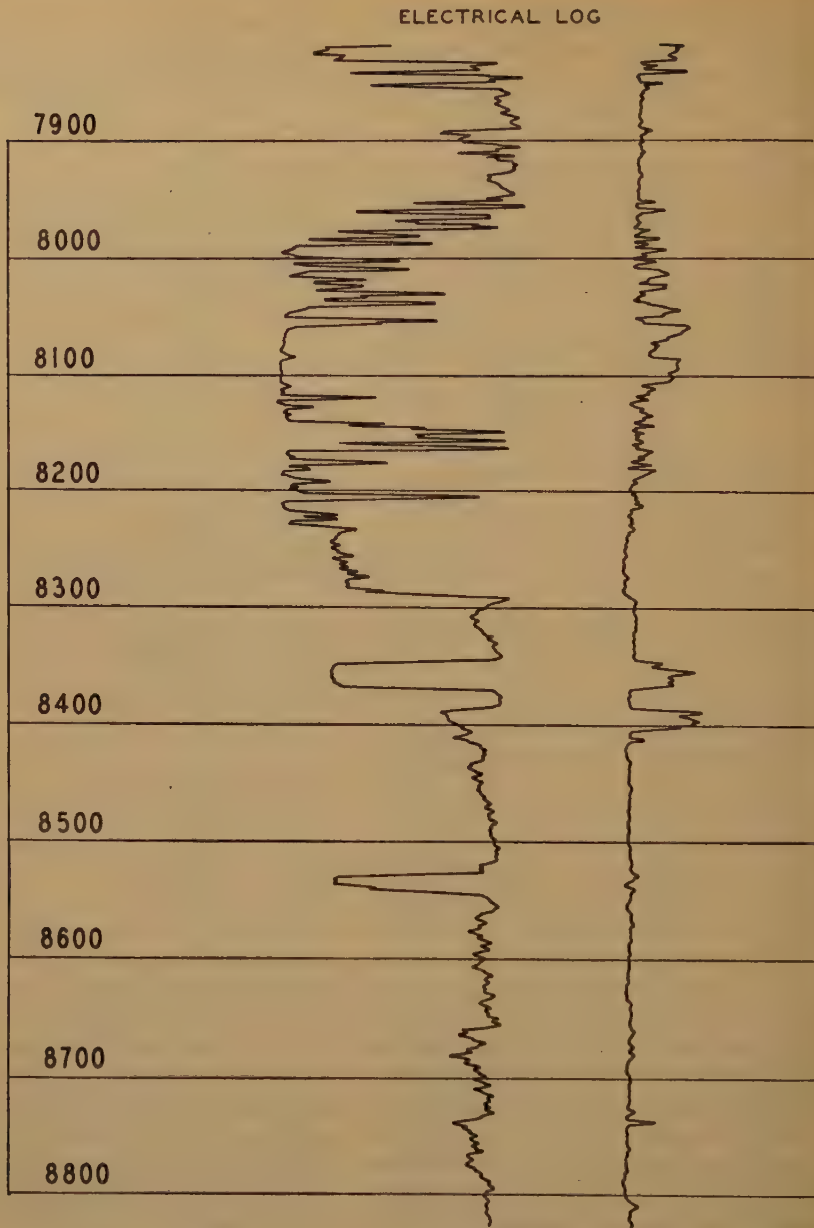
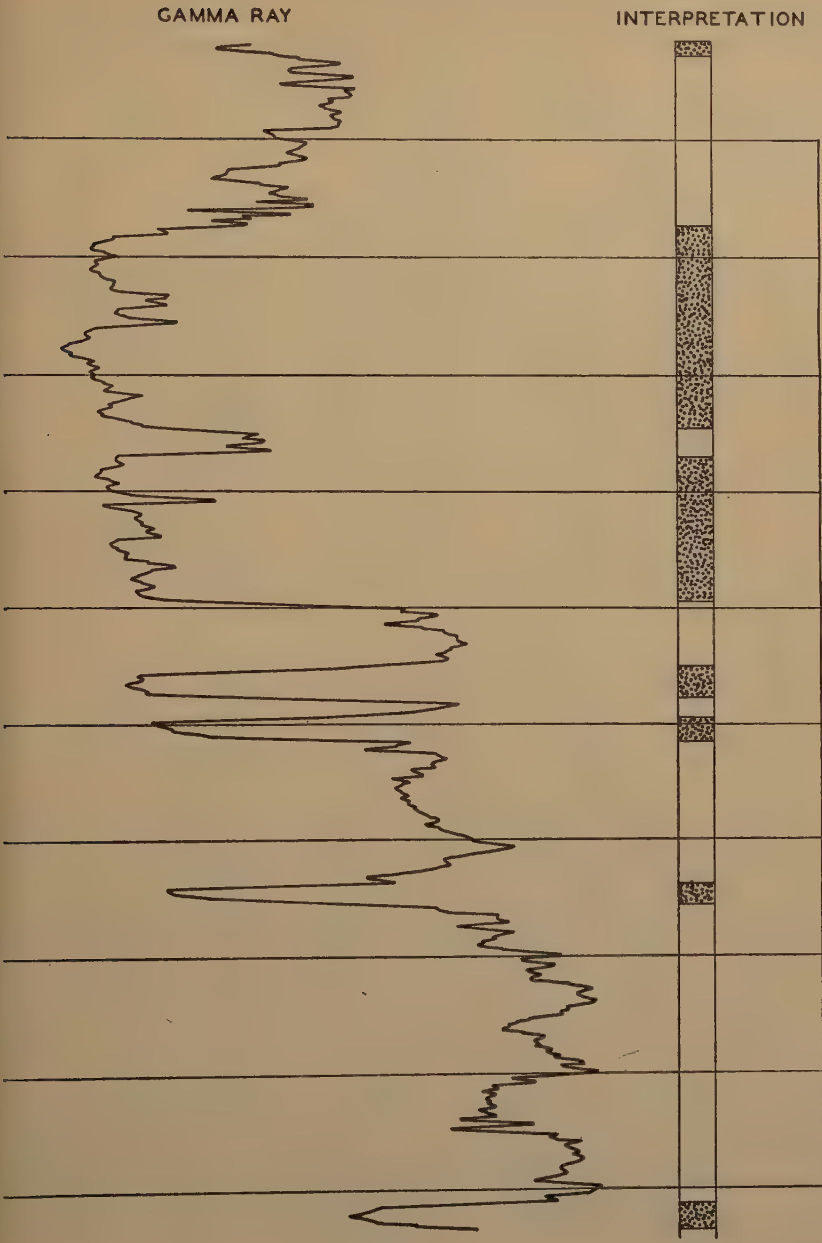


FIG. 14.—OBTAINING STRATIGRAPHIC



INFORMATION IN SALT-CONTAMINATED MUD.

possible to secure either of the radioactivity curves without regard to the composition of the mud.

Fig. 14 illustrates this condition in a wildcat well drilled in Assumption Parish, Louisiana. The characteristics of the mud were normal and six electrical logs were obtained successively as drilling progressed and the salt cap was penetrated. The salt lowered the resistivity of the mud to 0.4 at 93°F., and the final electrical log failed to define a known sand a few feet above the salt.

The casing was landed, and after the cement had been drilled out a gamma-ray log that covered the doubtful section was run from 8835.5 to 7820 ft. A comparison of the logs over this section shows the definition of the bottom sand on the gamma-ray log, which is masked out on the electrical log, and the agreement between the two logs on the upper sands, although there is some difference as to their depths.

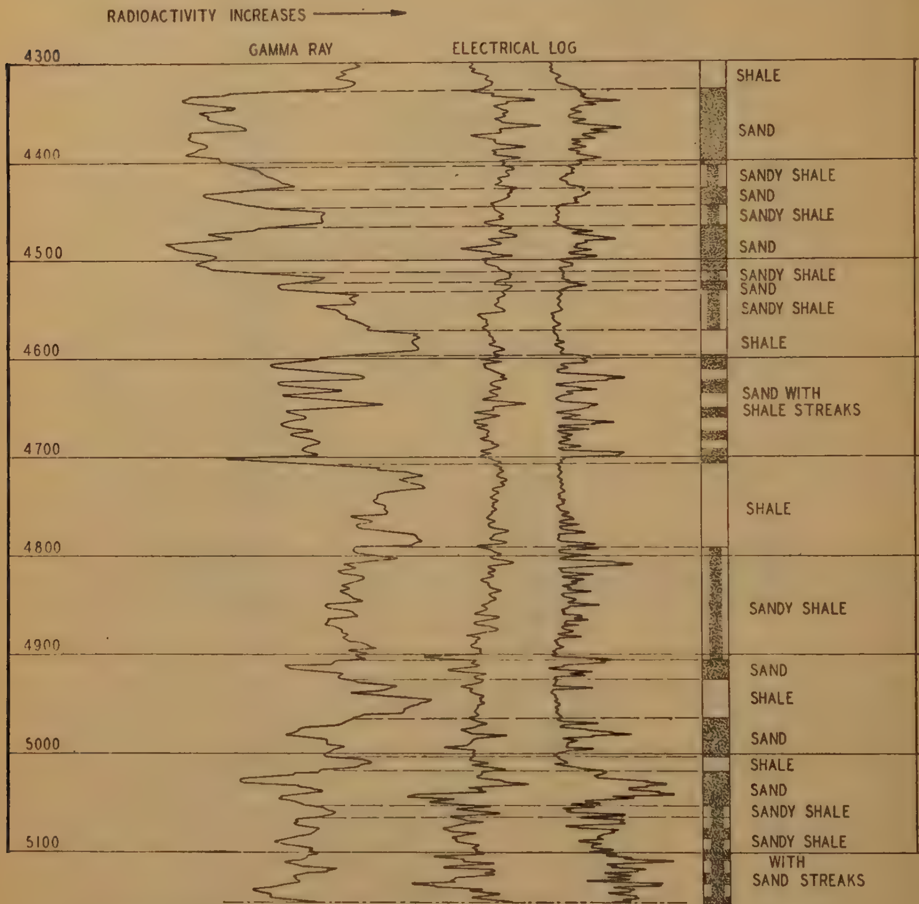


FIG. 15.—COMPARISON OF LOGS OBTAINED IN OIL-BASE MUD, CALIFORNIA.

Oil-base Drilling Fluid

Oil-base drilling fluid is used in several California fields to eliminate the infiltration of water where the productive zones are partially depleted and bottom-hole

pressures are low. Since oil is a dielectric substance, it offers greater electrical resistance, and thus makes it difficult to obtain a satisfactory electrical log.

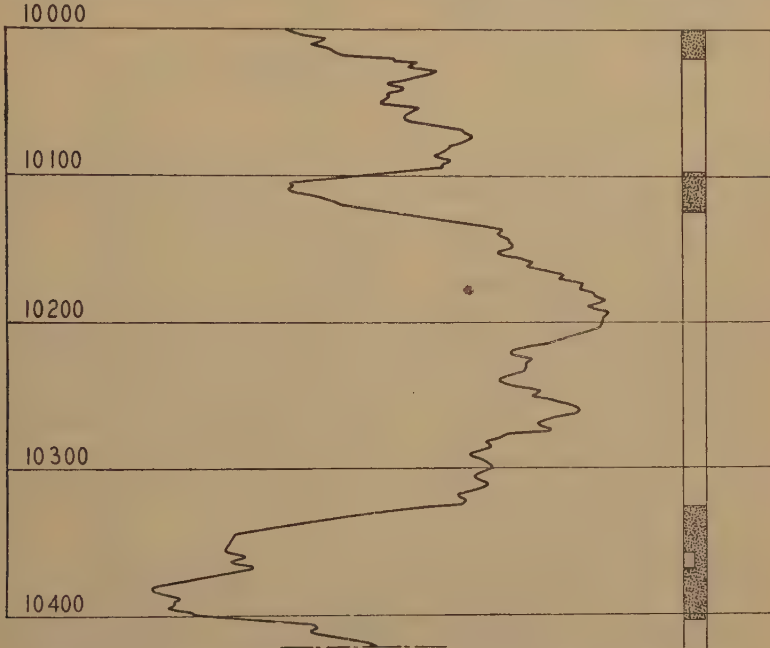


FIG. 16.—GAMMA-RAY LOG AFTER CASING IS SET, TEXAS GULF COAST.

In order to obtain correlation, electric logs have been run by using electrodes that make a sliding contact on the walls of the hole. The nature of this contact with the irregular formation changes in the walls of the hole is unsatisfactory, and tends to produce a curve that is sometimes difficult to interpret.

The gamma-ray log is independent of any contact with the walls of the hole, and reacts normally in oil-base drilling fluids, giving a clear, sharp, definition between sands and shales as shown in Fig. 15. Good correlations are obtained with neighboring electric logs of wells drilled previously with oil-base drilling fluid, and with other gamma-ray logs in the vicinity.

THREATENING BLOWOUT

Despite the extreme care and precautions normally observed in the drilling of deep exploratory wildcats, there is always the possibility that the unexpected penetration of an unknown high-pressure gas-bearing sand will upset the planned schedules and engineering procedure of electrical logging intervals, and mud controls.

When such a sand is penetrated the use of extremely heavy muds and the speeding up of operations leading to the introduction of casing usually prevents the accumulation of vital information on the bottom section of the hole normally obtained from cores and electrical logs. After casing has been set safely in such a well, a radioactivity log can be run to obtain neglected information, or as a check upon uncertain information relating to the type and depth of formations cased off.

Fig. 16 illustrates the results obtained under these conditions on a wildcat drilled on the Carrizo-Wilcox trend of the lower Gulf Coast. It was necessary to raise the mud weight while drilling below a depth of 10,000 ft., and to maintain it

approximately at 16.8 lb. per gallon. Under these conditions no electrical log was obtained and 5½-in. casing was set through the Wilcox formation. The gamma-ray survey was run after the cement plug was drilled, to supply additional information and to check the known data in the upper part of the hole. The entire log of the well was then complete, and correlation with subsequent tests was made easier.

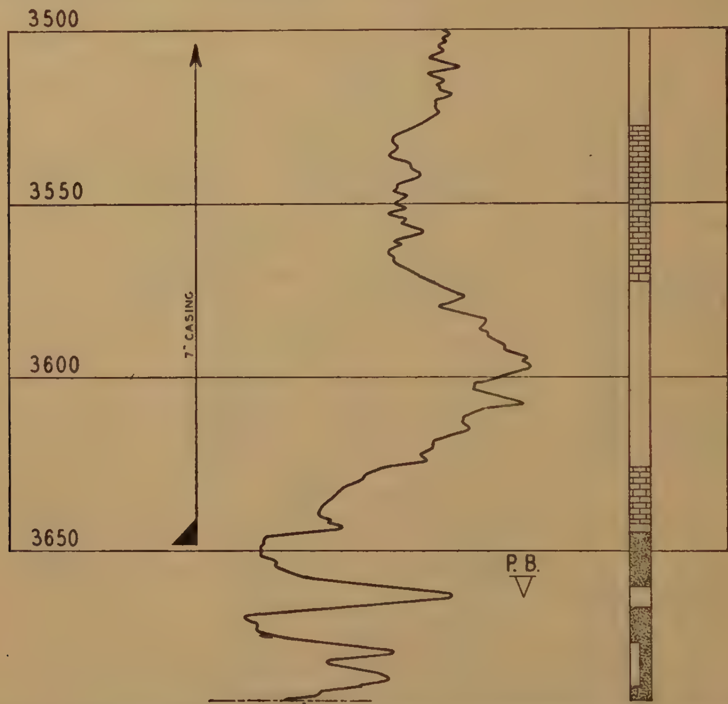


FIG. 17.—GAMMA-RAY LOG INDICATES PRESENCE OF PARTIALLY CASED-OFF SAND.

LOCATING CASING SEAT FROM GAMMA-RAY LOG TO PREPARE FOR SHUTTING OFF BOTTOM WATER

Fig. 17 shows a gamma-ray log of a well in the East Texas field, made to determine the exact depth of the casing seat before plugging back. The operator had aimed to set the 7-in. casing at the base of the Austin chalk for an open-hole completion. After several years of production, the well gradually went to water, and as a result, a greater volume of fluid had to be lifted to obtain the 20 bbl. per well allowable in the East Texas field. The well was producing 18 per cent of the fluid as bottom water at the time of the survey. The gamma-ray log shows the top of the Woodbine sand at 3645 ft., and by using the collar finder, a casing seat was located 3 ft. below the top of the Woodbine sand instead of at the base of the Austin chalk. After the well was surveyed and the situation studied, the well was plugged back to 3657 ft., and 15 per cent of the water production was eliminated. Production records in January 1945 showed only 3 per cent water. Future gun-perforating will permit a rejuvenation of the well when the open-hole zone has been depleted of its oil.

The records of other wells on this same lease with questionable casing programs were as follows:

Well	Production before Plug-back, Per Cent		Production after Plug-back
	Oil	Water	
A	67	33	Pipe-line oil
B	1	99	1.2 per cent water
C	65	35	Pipe-line oil
D	50	50	5.8 per cent water

Gamma-ray Log Used to Clarify Doubtful Measurements

Discrepancies in well-depth measurements continue to appear, and the problem of obtaining correct measurements has been receiving considerable attention by engineers in recent years. Not only has this problem been evident because of the present trend toward the development of relatively thin strata at greater depths, but in remedial work on old wells in the processes of primary and secondary recovery as well.

Much unnecessary squeeze cementing leads to the attempt to complete wells in zones where inaccurate depth measurements have been reported. Fig. 18 illustrates a typical problem in a Gulf Coast field. According to the gun-perforating record charted on the figure, the casing was gun-perforated from 8839 to 8842 ft., which is in the lower part of the sand, as indicated on the electrical log. The well tested pipe-line oil, and was produced for a time until subsequent remedial work was necessary to shut off bottom-hole water. After the original producing zone had been squeezed off, the well was gun-perforated several times between the depths of 8826 to 8842 ft., and on tests following each operation the well produced some oil with excessive quantities of salt water. The last two tests, between 8822 and 8832 and 8826 and 8833 ft., however, showed no production of oil or water.

The gamma-ray log was run to check the accuracy of the electrical log for the purpose of measurements. The producing zone was found somewhat lower than was indicated by the electrical log, accounting for the dry tests that were made in shale strata.

The well was gun-perforated again from 8835 to 8839 ft., and it was completed to produce commercial quantities of oil with some salt water.

Casing-collar Locator

Experimental work is being done to develop an electrical collar locater that records the depths of casing collars simultaneously with the gamma-ray log.

The electrical collar detector is an accessory to the subsurface gamma-ray instrument, and is designed to transmit electrically on to the recorder at the surface an indication of the location of each collar. The record for each is made by an independent pen on the same chart with the gamma-ray log. Fig. 19 is an illustration of the casing-collar log together with a typical gamma-ray log.

This device offers a method of obtaining extreme accuracy in well-depth measurements. The formations defined by the gamma-ray log may be correlated definitely with permanent bench marks that are less than half a joint of casing away from a zone of interest. The same casing collars can be relocated by means of a collar-locating device attached to other tools to establish a zone of interest at any future time. Subsequent testing or cement jobs that normally change the apparent total depth of a well will have no effect on the relocation of the collars.

Conclusions

The versatility of radioactivity well logging is shown by the numerous examples in this paper. This new tool should be a great aid to the oil industry because it is adaptable to a variety of problems that are met either in new or old wells.

Acknowledgment

The writers gratefully acknowledge the cooperation of numerous geologists and

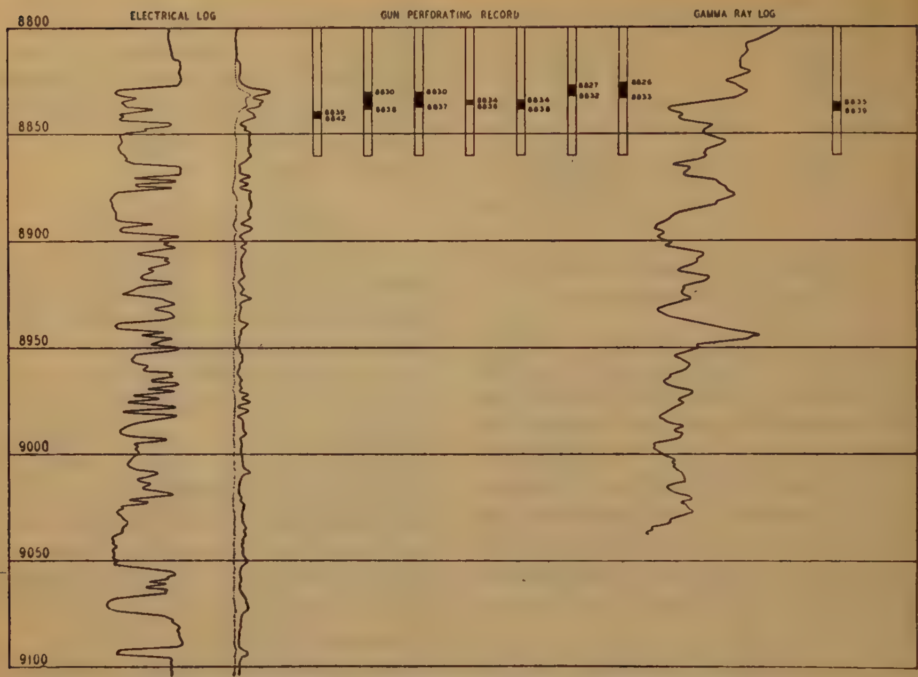


FIG. 18.—GAMMA-RAY LOG CLARIFIES MEASURE DISCREPANCY.

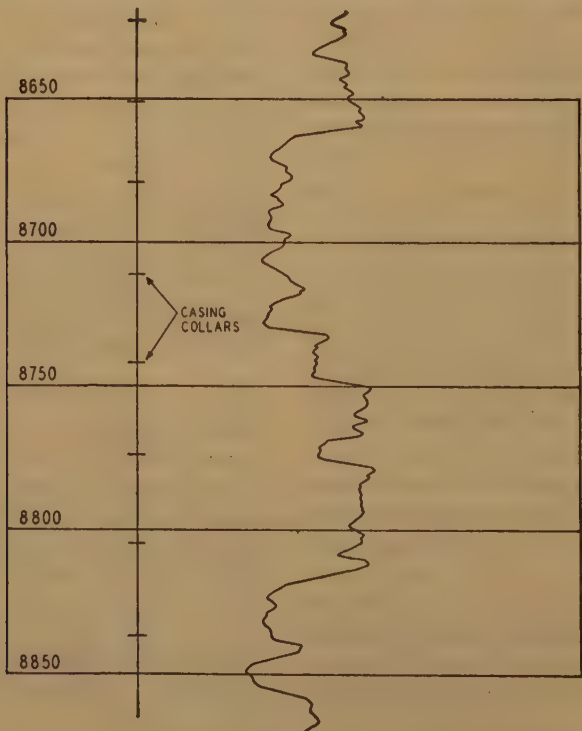


FIG. 19.—LOG OF ELECTRICAL COLLAR LOCATOR RECORDED SIMULTANEOUSLY WITH GAMMA-RAY LOG.

engineers associated with independent and major oil companies who made this study possible by releasing logs and production data. They thank Mr. Charles B. Carpenter, Bureau of Mines, Dallas, Texas, and Mr. Henry C. Cortes, Magnolia Petroleum Co., Dallas, Texas, for reviewing and criticizing the manuscript and the Messrs. J. D. Hughes and A. B. Winter for technical assistance. They appreciate the permission of the Lane-Wells Company for publication of the paper.

Selected Bibliography

1. Howell and Frosch: Gamma Ray Well Logging, *Geophysics* (March 1939) **4**.
2. Westby and Scherbatskey: Well Logging by Radioactivity. *Oil and Gas Jnl.* (Feb. 22, 1940).
3. Green and Fearon: Well Logging by Radioactivity. *Geophysics* (July 1940) **5**.
4. W. L. Russell: Well Logging by Radioactivity. *Oil Weekly* (Nov. 11, 1940).
5. B. Pointecorve: Neutron Well Logging *Oil and Gas Jnl.* (Sept. 11, 1941).
6. W. L. Russell: Well Logging by Radioactivity. *Bull.* Amer. Assn. Petr. Geol. (Sept. 1941).
7. L. C. Beers: Radioactivity Logging through Casing. *Petr. World* (Nov. 1941).
8. P. Weaver: A Theory of the Distribution of Radioactivity in Marine Sedimentary Rocks. *Geophysics* (April 1942) **8**.
9. Radioactivity Logging Proves Help in Reworking Old Wells. *Oil and Gas Jnl.* (June 25, 1942) 140.
10. Russell and Downing: Neutron Logs Find Porous Zones in Western Kansas Limestones. *Oil and Gas Jnl.* (Aug. 6, 1942).
11. J. L. P. Campbell: Gamma Ray Logging in East Texas. *Petr. Engr.* (Jan. 1944).
12. E. H. Short, Jr.: Use of Gamma Ray Curves Increases Possibility of Successful Workover. *Oil and Gas Jnl.* (March 16, 1944) **22**.
13. G. F. Shepherd: Use of Gamma Ray Logs in Measurement Problems. *Oil Weekly* (May 8, 1944).
14. R. E. Fearon: Gamma Ray Measurements. *Oil Weekly* (June 4, 1944).
15. R. E. Fearon: Neutron Bombardment of Formations. *Oil Weekly* (June 11, 1945).
16. The following articles were published in Tomorrow's Tools Today, by Lane-Wells Co.:

Volume 8

L. C. Beers: Radioactivity Logging Reclaims Depleted Wells in Long Beach Field, Calif.
R. Cantrell: Radioactivity Logs Aid in Making Coast Workovers Worth While.
A. B. Winter, M. C. Bowsky, and J. C. Stick, Jr.: Correlation between Electrical Logs and Radioactivity Logs.
J. L. P. Campbell: Locating Cased-off Production in Old Wells.
A. B. Winter: Use of Neutron Curves.

Volume 9

J. L. Neale: Proper Completion Assured by Radioactivity Logs.
J. C. Barcklow: Adaptability of Radioactivity Logs to Limestone Zones in Old and New Wells.
R. L. Alder: Recompletions Based on Radioactivity Logs.
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Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics

By G. E. Archie*

(Dallas Meeting, October 1941)

Abstract†

Data given in this paper indicate that certain relations exist between different characteristics of sandstone. These relations are not rigid, for all sandstones are more or less heterogeneous. Not every increment of a given horizon follows exactly the relationship; however, studying a reservoir as a whole from a large number of samples, definite trends are found to exist. Apparently nature's processes of sedimentation and diagenesis are such as to give some degree of uniformity. Average relationships are valuable because electrical measurements in a borehole comprise a considerable volume of rock near the hole. Also, it is desirable that a given producing reservoir be studied as a unit.

In a permeable reservoir whose pores are filled with a saline solution, it was found that the total porosity and the type of sandstone influence the relationship between its electrical resistivity and the R_0 and the resistivity of the brine R_w. The relation can be expressed by the following empirical equation,

$$R_0 = R_w\theta^{-m} \qquad [1]$$

where θ is the porosity expressed as a fraction and the numerical value of the exponent lies between 1.8 to 2.0 for consolidated sandstones, and is about 1.3 for clean, unconsolidated packs. This equation indicates that an appropriate electrical log can be used to estimate the porosity of a saline water-bearing reservoir when R_w and the type of rock are known.

The fraction R_0R_w is called the "formation resistivity factor." It reflects the effect of the nonconducting rock structure on the resistivity of the salt water that fills the tortuous paths through which the electricity must pass. The formation resistivity factor F is found to be related to permeability k. In this case the type of rock plays an important role, as shown by the relation

$$F = ak^{-b} \qquad [2]$$

where the values of a and b must be determined experimentally for each horizon. Therefore Eq. 1 rather than Eq. 2 is used when it is desired to determine the value of F, because small changes in rock structure particularly in the pore size are not critical.

Another useful relation,

$$R = R_0S^{-n} \qquad [3]$$

where R = resistivity of rock when partially saturated with brine and partly with oil or gas, S = fraction of the pore space filled with brine, and n equals approximately 2 for both unconsolidated and consolidated sandstone, shows that the connate water of an oil or gas reservoir can be estimated in situ from a resistivity log.

Equation 3 shows that in order to estimate the water content of a reservoir a knowledge of R and R_0 is essential. The first value can be obtained from the electrical log when all factors influencing the resistivity curve can be properly taken into account. The latter may be obtained when a log is available on the same horizon where it is entirely water-bearing and has

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† The entire paper was printed in *Trans.* A.I.M.E. (1942) 146, 54.

the same average porosity. In this case the water saturation can be estimated from Eq. 3 without further knowledge about the reservoir. When R_0 is not available from a log, it can be calculated from Eq. 1.

The resistivity scale used by the electrical logging companies is calculated assuming the electrodes to be points in an infinitely thick homogeneous layer. Therefore, the values recorded must be corrected for the presence of the borehole, thickness of the layers in relation to the electrode spacing, and any other condition different from the ideal assumptions used in calculating the scale. Obtaining the true value of resistivity of rock from an electrical log is generally complicated by several of these factors, which must be thoroughly appreciated before reliable interpretations can be made.

Calculations show that if the resistivity of the formation is less than 10 times the resistivity of the mud, the effect of the borehole will generally not be great.

The thickness of the layer must be large in comparison with the electrode spacing, otherwise "thin-layer effects" arise. In simple cases these aberrations can be calculated and an insight into the behavior of these curves is useful in attempting to unravel the complicated performance of large penetration electrodes in thin layers.

It is desirable to use as small a spacing as possible to reduce thin-layer complications; however, by doing so the depth of investigation is reduced so that invasion of the mud filtrate has an appreciable effect on the resultant or observed resistivity value. Invasion of mud filtration is probably the most serious factor limiting the quantitative use of electrical logs today.

Factors Influencing Electrical Resistivity of Drilling Fluids

By John E. Sherborne,* Member A.I.M.E., and William M. Newton†

(Los Angeles Meeting October 1941)

Abstract‡

The value of the electric log as a means of interpreting underground structures has been increasingly demonstrated by its almost universal present-day use. It becomes important, therefore, to be able to evaluate the factors that affect the values obtained.

By far the greatest number of electric logs are measured today in boreholes filled with rotary mud, the properties of which may exert an important influence on the electric log. In an effort to establish what the order of magnitude of such effects might be, a series of investigations was made in the laboratory and the field.

Apparatus suitable for either field or laboratory use was designed and a procedure established for determining the factors that affect the resistivity of drilling muds over a wide variation in mud condition. Five muds representative of the types of clay-base muds employed in California were tested and the following observations were made:

1. The effect of raising the temperature from 80° to 180°F. is to decrease the resistivity of the mud or filtrate approximately 50 per cent.

2. The resistivity of the mud in most cases closely approximates that of its filtrate.

3. The change in the resistivities of muds caused by the addition of chemical is not the same function of the amount of chemical added for each mud.

4. The effect produced by increased sodium chloride content is to reduce markedly the resistivity of the mud and its filtrate.

5. Weighting materials, such as baroid and limestone, tend to increase the resistivity of drilling mud.

6. Cement and counteracting reagents reduce mud resistivity.

The results of the investigation indicate that the mud resistivity is materially affected by the addition of electrolytes whether these are added for the purpose of conditioning the mud or enter the mud when salt beds or highly saline structures are penetrated. It should be observed, however, that the magnitude of the effect produced upon the electric log by changes in mud resistivity is also dependent upon the relative salinity of the water encountered in the formation being logged.

The laboratory data are supplemented by field data, which indicate that both the self-potential and resistivity curves are influenced by mud resistivity.

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‡ The entire paper was printed in *Trans.* A.I.M.E. (1942) **146**, 204.

Influence of Geophysics upon Geology Curricula

The papers that appear on pages 326 through 367 were presented at two joint meetings of the Mineral Industry Education Division, Geophysics Committee, the American Geophysical Union and the Committee on College Curricula of the American Association of Petroleum Geologists, at the A.I.M.E. meeting in New York on Feb. 17 and 18, 1941. At the first meeting, the Mining Geology Committee, the Society of Economic Geologists and the Committee on Applications of Geology of the American Association of Petroleum Geologists also took part.

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Influence of Geophysics and Geochemistry on the Professional Training of Geologists

By W. C. Krumbein,* Member A.I.M.E.

(New York Meeting, February 1941)

Geological problems are approached from a geometrical (space relations) viewpoint, a kinematical (time sequence) viewpoint, or a dynamical viewpoint. The first two require sound training in conventional geology and in field methods. The third approach requires a solid foundation of chemistry, physics, and mathematics. Modern training for geologists should include close integration of basic sciences with geological principles.

Introduction

Our knowledge of the earth has increased tremendously during the last half century. We know more about its surface configuration, the distribution of its natural resources, the procession of living forms that inhabited it in the past, the chemical composition of its oceans, the areal distribution of its surface rocks, the movements of its atmosphere, and so on. Not only do we know more facts about the earth, but we have a better understanding of the processes that take place on and within it, such as the nature of earthquakes, the thermodynamics of the atmosphere, the chemical equilibria involved in the formation of igneous rocks, the mechanics of stream flow, the dynamics of the earth's origin, and so on.

Many sciences contributed to the sum total of this knowledge, including such established disciplines as geology, geography, physics, chemistry, astronomy, biology. Out of this accumulation of new knowledge grew also a group of new sciences, such as seismology, oceanography, meteorology, volcanology, hydrology. Collectively these latter are known as the geophysical and geochemical sciences, and to a large extent they began as branches of geology. Until the turn of the century, for example, the study of earthquakes (seismology) was a part of geology, although as early as 1846 Mallet, a physicist, had suggested that the subject could be investigated by elastic-wave theory. Comparatively little progress was made along these lines until the seismograph was developed near the turn of the century; since then, additional earthquake data have accumulated rapidly, but more important, the interpretation of these data essentially has kept pace with their accumulation.

In similar fashion, meteorology was generally considered a branch of geology as recently as one or two decades ago. Considerable progress had been made in such aspects as weather forecasting, but the science dates its recent rapid rise from the year 1911, when Bjerknes first applied the principles of dynamics to the analysis of air masses. The rapid development of such disciplines as oceanography, volcanology and hydrology was due in part to the application of principles of chemical equilibrium, of dynamics, and of thermodynamics to earth problems, by men who were essentially physicists or chemists by training. The last half century, therefore, and particularly the last two decades, saw the influx of numerous chemists and physicists into the realm of the earth sciences.

In the meantime the main body of geology itself showed a marked growth, and

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the number of active workers in that science, entirely aside from those in the newer sciences, increased beyond anticipation. With a large number of men working on earth problems, and in view of the diversity of their interests and training, various questions have arisen regarding the relations of the several new sciences to each other and to geology. The writer proposes to look into this question, as it affects the kind of training professional geologists should receive.

Relations among Earth Sciences

A term that has received some acceptance among scientific workers is *earth science*, which refers in general to those sciences whose realm is the study of earth materials and earth phenomena. The earth sciences include not only geology and geography, but geophysics and geochemistry, with all their subdivisions. In addition, *soil science* is included, which itself is divided into *soil physics*, *soil chemistry*, and *soil biology*. The present paper is not concerned with the whole domain of the earth sciences; its main interest lies with geology, geophysics, and geochemistry.

Geology is defined usually as the science that deals with the history of the earth and its inhabitants, as they are revealed by the rocks and their enclosed fossils.[1,2] A number of aspects of the science are recognized; Chamberlin and Salisbury distinguished three main subdivisions: (1) structural geology, which deals with the form, arrangement, and internal structure of rocks; (2) dynamical geology, which deals with the processes of geological change; and (3) historical geology, which, with the aid of other branches, seeks to give a chronological account of the events in the earth's history. Further subdivisions of the science, which concern specialized aspects, include such disciplines as petrology, paleontology, economic geology, physiography, stratigraphy, mineralogy, and such recent developments as paleogeography and paleoecology. In the past, at least, such disciplines as meteorology, volcanology, and seismology were considered subdivisions of geology, and there may be some basis for the contention that some of them still are. How an individual science is classified is perhaps less important than its content and methods, and its relation to other sciences.

In 1938 Hubbert[3] analyzed the relations among the several major sciences, and showed an order of dependence among them. Geology, according to Hubbert, may be considered as the science of the nature and movements of matter and the accompanying energy changes on and within the earth. In this sense geology is a dependent science, inasmuch as it is concerned with a special case of the behavior of matter and energy. Whether or not one accepts Hubbert's definition, there is no doubt that the development of geology depends to a large extent upon the application of methods and principles from physics, chemistry, astronomy, and the biological sciences.

The relations among some of the earth sciences are shown graphically in Fig. 1. The upper part of the chart includes the several subdivisions of geology as they are generally recognized today. The lower part of the diagram, under the dashed line, includes the disciplines that constitute sections of the American Geophysical Union.* Beneath the separate disciplines rests the foundation of the basic sciences. Principles from these basic sciences filter through the earth domain, and feed into the several subdivisions of the earth sciences. Likewise, biological principles enter certain aspects of the earth sciences. As a start, it is convenient to work downward from the top of the diagram.

The several divisions of geology are arranged in an order that approximately

[1] References are at the end of the paper.

* The American Geophysical Union was established in 1919. Its eight sections are Geodesy, Seismology, Meteorology, Terrestrial Magnetism and Electricity, Oceanography, Volcanology, Hydrology, and Tectonophysics. See *Trans.* Amer. Geophys. Union (1940) pt. 1, 3.

reflects their interrelations. For example, the complete analysis of a stratigraphic problem may require an application of principles of paleontology, of petrology

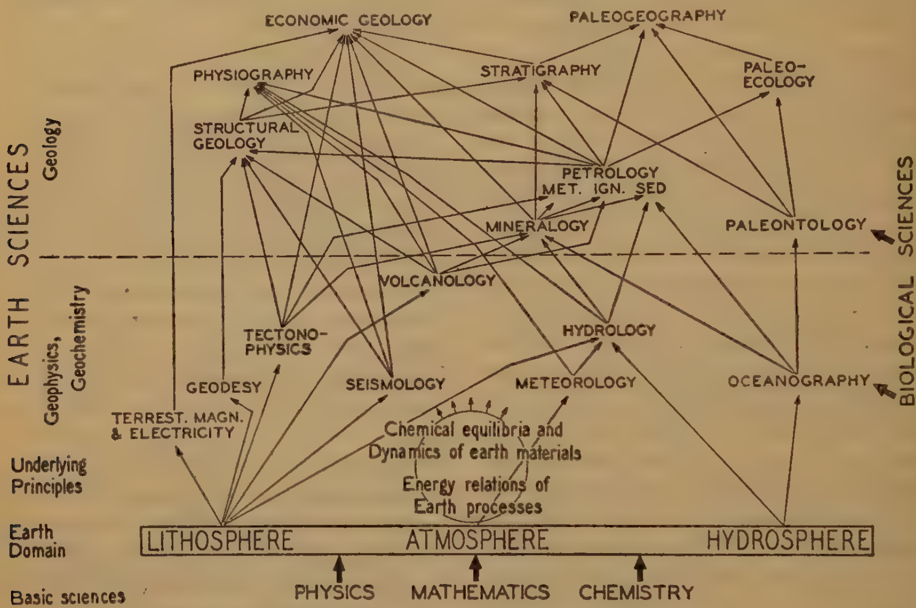

FIG. 1.—RELATIONS AMONG SOME EARTH SCIENCES.

(especially the sedimentary rocks), of structural geology, and of other branches of the main science. Economic geology solves its problems by applying principles of petrology, of structural geology, and so on. Physiography uses principles of petrology, of structural geology, and requires an understanding of the gradational processes (hydrology is an example). Thus the arrows in the diagram represent for the most part a unidirectional dependency of some branches on others. A structural geologist, concerned with the geometry of folds, for example, requires no knowledge of stratigraphy; to map structures in the field, however, he must be able to arrange a stratigraphic section and to locate key beds. What the diagram seeks to convey is a dependency in terms of principles rather than methods.

The relations among the disciplines below the dashed line in Fig. 1 are more difficult to evaluate. The writer used several criteria in this evaluation. On the one hand, some of the disciplines are closely related to a single part of the earth, as seismology to the lithosphere. Others, like hydrology, may be related to all three parts of the earth. On the other hand, some of the disciplines, whether they are related to one or another part of the earth, are removed more or less from the conventional domain of geology in their method of attacking problems. Where dependencies exist, the relative levels may be determined by that factor.

The writer is aware that his diagram is not completely satisfactory. The chart is presented as a first approximation to the structure of part of the earth sciences, and should be used for its "mass effect" rather than for its reflection of the exact state of the sciences in 1941.

The unidirectional nature of the arrows in the diagram is not wholly justifiable, although in general they indicate the direction of flow of principles from divisions

more basic to those more dependent. However, sometimes principles established in a more dependent field may influence conclusions drawn in a less dependent field, because the test of many analytical theories applied to earth phenomena is whether they agree with the body of observed geological facts. For example, early estimates of the age of the earth, based on assumptions of a continuously cooling globe, were strictly rigorous in their analytical methods, but had to be modified when evidences of pre-Cambrian glaciation were brought forward.

In a reversed sense the arrows in Fig. 1 also tell a story. Follow any arrow backward, and in general it will indicate the direction of flow of subject matter from the conventional fields of geology to the geophysical or geochemical disciplines that now claim them. Exceptions to this are found in such subjects as oceanography and meteorology, which moved bodily downward as units.

The large number of arrows flowing through the diagram indicates that no single subdivision of the earth sciences is wholly remote from the others, because indirectly at least they are related by some more dependent division. Although the arrows show many relations which at best are indirect, there is in fact a very close relation among all of these sciences if one penetrates to a still lower level. Immediately above the block that represents the earth domain are three fundamental principles of the basic sciences. These are the Dynamics of Earth Materials, the Chemical Equilibria of Earth Materials, and the Energy Relations of Earth Processes. Lines from one or more of these principles should extend outward to every one of the earth sciences. To avoid crowding the diagram, these lines are merely indicated by the small arrows that point away from these principles. The relation of these principles to geophysics and geochemistry is more directly seen, but already some of the specific principles have been applied to such typically geological fields as economic geology, structural geology, and petrology.

In terms of certain underlying principles that apply to all matter, whether on the earth or not, there is a true unity among the separate disciplines that constitute the earth sciences. There is one other unifying factor, which should not be overlooked: *each of the disciplines is closely related to the earth.* No matter how far afield his investigations may take him, the worker must return periodically to a consideration of some part of the earth. However general the applications of dynamics, chemical equilibrium, and energy relations, the earth sciences are concerned only with their application to earth problems. This unity, combined with the various levels of dependency among the separate disciplines, has an important bearing on the kind of training professional geologists should receive.

In the first place, the relative degrees of dependency shown in the diagram indicate that it is more important for a worker in the dependent sciences to know the subject matter and methodology of the less dependent sciences than for a worker in the less dependent to have information on the dependent sciences. For example a meteorologist need not know one rock from another in order to become an expert in his field, but a sedimentary petrologist must know something of the dynamics of the atmosphere if he is to understand the factors that control the transportation and deposition of sand and dust by wind. Second, the interlocking of the geophysical and geochemical disciplines through the geological sciences indicates that it is more feasible for workers in the dependent sciences to integrate the entire field of the earth sciences than it is for workers in the less dependent sciences to do so. To achieve this integration, however, the geologist must be sufficiently well trained in the basic sciences to apply the principles of dynamics, of chemical equi-

libria, and of energy transformations to his geological problems.

Design of a Geology Curriculum

In considering the kind of training that present-day students of geology should have, the safest procedure is to return directly to first principles. What is the subject matter of geology, and what is the geologist's approach to this subject matter? Fundamentally the earth is the geologist's domain. Geological problems may concern mainly the lithosphere, but the atmosphere and hydrosphere also receive attention. The geologist approaches his problems in a variety of ways, but basically these may be reduced to three, which correspond roughly to the historical development of the science. The first approach is the *geometrical* approach, in which the geologist collects his facts and reports what he sees. This approach is mainly descriptive; he lists the minerals in a rock or the fossils in a given bed, or he arranges his outcrops into a geological map. In general, it is the space relations that are given: the problem is set up in its proper perspective. Interpretive elements may enter this work, such as the reconstruction of subsurface structures from surface data.

The second approach is *kinematical*, in which the geologist is interested in the order in which events occurred. The sequence of mineralization in a vein, the succession of deposits in a sedimentary basin, the order of appearance of fossils in rocks are examples. This is the approach of historical geology—of events as functions of time. The time relations may be described fully and accurately without knowing why that particular sequence of events occurred, and not some other; that is, the laws that control the time relations need not be known, nor even investigated in this second approach. For example, one may observe that the sequence of eruptive rocks in a given region is from rhyolite to basalt—i.e., that the silica content of the lava decreased as a function of time—and yet he may not know what particular chemical equilibria were involved in this sequence.

The third approach to earth problems may be called the *dynamical* approach, using that word in its strictest physical sense. This approach seeks to answer the physical why of the problems. Why did a particular sequence of events occur; why does a given igneous rock contain a particular mineral suite; why did a fossil fauna evolve in this direction and not some other? The physical why of the problem involves a study of the forces that operated to produce certain ends. Such a study must include the energy of the particular system, the dynamics of the material, and the chemical equilibria that may have occurred. For example, when the geologist penetrates beyond the description of an anticline and the relative time of folding to the forces that produced the anticline, he is at once concerned with the laws of elasticity, of plasticity, of gravitational forces, and the like. Similarly, when one investigates the reasons why particular minerals occur in certain igneous rocks, he enters the field of phase equilibria, and uses the concepts of chemical equilibrium to solve his problem.

To a large extent present-day geology is concerned with the first two approaches to earth problems, but a large amount of work is being done on the third aspect. In general, these problems are being attacked by geochemical and geophysical methods, and a number of geologists are in the forefront of such work. Both historically in the development of the science, and from present indications in geology, this third approach will assume relatively greater importance as time goes on.

In terms of the foregoing analysis, it may be said that with respect to the first and second approaches, geology is primarily a field science. The geologist must be able above all else, perhaps, to do field work; that is, he must be able to map an area, to work out the stratigraphic section, to

describe the structures present, and to arrange the geological events that occurred in the region in their proper time sequence. Finally, the geologist must be able to draft a presentable map and to write an intelligible report.

These basic aspects of geological work require training in field methods, in plane-table mapping, in trigonometry and descriptive geometry, in drafting, and in English, in addition to fundamental training in mineralogy, petrology, structural geology, physiography, stratigraphy, economic geology, and paleontology. These several items may be considered the minimum essentials if the student is to have any competence either in general geology or in one of its more specialized branches.

A present-day student with this training, and no more, is capable of doing the routine work of geology, but in general he will be capable neither of advancing very far in his profession nor of contributing significantly to the progress of the science. Modern views in geology, as they are influenced more and more by the third approach to geological problems, require a sufficient breadth of training to see the full implications of the field evidence collected. It is here that the geologist's training must go beyond geology itself, and penetrate into the basic sciences of chemistry and physics. In short, the extent to which the geologist is able to use the dynamical approach to earth problems depends upon how much training in the basic sciences he carries with him. More than that, training in physics, chemistry, and mathematics develops a critical judgment that is invaluable in the study of any scientific problem.

Adequate training for the general geologist in the basic sciences should include chemistry through quantitative analysis and physical chemistry. His training in physics should include the fundamentals of mechanics, of heat, of electricity, and of light. Beyond this, his training should emphasize classical physics as opposed to modern quantum physics; analytical mechanics at least is a necessity. To understand the theoretical side of the basic sciences, mathematical training should extend through differential equations.

To supplement this training in his own and in the basic sciences, the professional student of geology should have an understanding of the modern world, and of the heritage of culture possessed by mankind. This requires that he receive some training in the social sciences, in the humanities, and in natural sciences other than those specifically mentioned. The geologist plays an important role in the development of sound conservation policies, for example, and his usefulness in this respect is measured in part by his understanding of the broader aspects of the social sciences.

Five-year Program

Any consideration of professional training in geology at the present day must be predicated on a five-year program. The opportunities open for students with a bachelor's degree alone are limited, and apparently become more limited with time. A master's degree is the minimum essential for professional work if the student is to secure a desirable position, and have an opportunity to rise in his profession. The curriculum to be described is based on such a five-year program, leading to the degree of Master of Science.

Table 1 is a possible curriculum based on the subjects specifically mentioned in earlier paragraphs. During the first two years the student acquires his general education, including some aspects of all the major disciplines, which consist of the humanities, the social sciences, and the natural sciences. The foundations of his training in geology, physics, chemistry, and mathematics are also laid. In the student's next two years he receives most of his professional geology training, and the remainder of his basic sciences. In the fifth year the student

finishes his fundamentals and has three subjects of his own choice, which include a modicum of specialization for his master's degree. The curriculum is based on the quarter system, although the equivalents may be expressed on a semester basis. The conversion factor is shown in the footnote to Table 1.

Table 1.—*Curriculum for Physical Geology*

Year	Subject	Number of Courses[a]
First	Mathematics (trigonometry, college algebra, analytical geometry)	3
	English composition	3
	Humanities (history, culture, philosophy)	3
	Biological sciences (botany, zoology, etc.)	3
Second	Introductory geology (processes, economic, historical)	3
	Introductory physics (mechanics, electricity, heat, and light)	3
	College chemistry (general, qualitative analysis)	3
	Social Sciences (economics, political science, etc.)	3
(Summer session: field course in geology)		
Third	Mineralogy (crystallography, optical mineralogy, determinative mineralogy)	3
	Descriptive geometry, drafting, plane-table mapping	2
	Calculus (differential, integral, and differential equations)	3
	Analytical mechanics	1
	French or German	3
Fourth	Advanced fundamentals: physiography	1
	Paleontology (morphology, index fossils)	2
	Economic geology	1
	Chemistry (quantitative analysis, physical chemistry)	2
	Petrology (igneous, sedimentary, metamorphic)	3
Fifth	Advanced fundamentals (stratigraphy)	2
	Structural geology	1
	Economic geology (choice of ores, oil, etc.)	1
	Physics and chemistry of the earth	3
	Thesis subjects (courses or research)	2

[a] A course consists of approximately 44 class hours. If the subject includes laboratory work, about 77 hours are required for class and laboratory.

ing. Such specialization should appropriately come during the subsequent two years, for students who continue their studies beyond the master's level. Courses at these higher levels may include further training in particular fields of geology, together with such additional work as may be required in the basic sciences. A total of 18 additional quarterly courses is usually taken, and among these some ratio may be used for geology and basic science courses. It is also highly desirable that a series of courses on the geophysical and geochemical disciplines of Fig. 1 be developed, to be taught by specialists in those fields. Some of these courses would be required of all advanced students; others would be available for specialization in certain fields.

A detailed examination of the curriculum indicates that most of the courses are available in any university, and their content is self-explanatory from their titles. An exception to this is the fifth-year sequence on the physics and chemistry of the earth. This is a set of three courses designed to integrate the student's work in geology and in the basic sciences with the geophysical disciplines shown in Fig. 1. These courses are to be offered by the geology department, and are to be taught by geologists qualified in the geophysical and geochemical disciplines; or directly by geophysicists and geochemists. Further details about the courses are given later.

The five-year curriculum does not permit much specialization in the geologist's train-

In summary, then, it is possible to approach the problem of training geologists purely from first principles, and this approach leads to the conclusion that adequate training for modern geological work can be included in a five-year program. It is interesting to see whether the conclusions

reached regarding the required training for geologists agree in general with the findings of other writers on the subject. No exhaustive review of the literature was made, but several articles shed an interesting light on the question.

Opinions of Earlier Geologists

About 20 years ago a series of editorials appeared in *Economic Geology*, in which various writers expressed their views about the training of geologists. Lindgren,[4] in 1919, expressed the opinion that an economic geologist should really be trained in engineering: "it goes without saying that he must know his fundamental sciences, mathematics, chemistry, physics." In a later article[5] he went into more detail on the educational requirements for geologists. He deplored the fact that some universities award a degree in geology with little reference to the fundamental sciences, and he cites examples in which students are permitted to take nearly every course in geology and yet are not even required to take such subjects as trigonometry and descriptive geometry. Among requirements for the bachelor's degree Lindgren suggests English, history, logic, and language. Physics and chemistry should be insisted upon, including quantitative analysis. His requirements in mathematics are interesting in the light of modern developments—he considered calculus and differential equations "indispensable." Among geological subjects he lists geology, paleontology, mineralogy, petrology, economic geology. Topographic surveying is a necessity.

Brock,[6] also writing in 1923, has no hesitancy in saying that in his opinion geologists should receive engineering training in their undergraduate days, with postgraduate work in geology. He favors this approach because it gives the student his mathematics and various sciences, his drafting and surveying, and the student acquires the engineer's concrete view of problems. Brock lists paleontologists as well as physical geologists among his students who stated that their engineering training was the least dispensable part of their work.

These several examples emphasize the point that leaders among geological teachers have been concerned with the lack of basic sciences in geology curricula. Unfortunately, it seems that little has been done about these suggestions, and the process of training geologists continues along its traditional lines. In the 20 years since Lindgren and Brock wrote their articles, however, geologists have seen the withdrawal of several disciplines from their own ranks. The American Geophysical Union was established in 1919, but its membership grew most rapidly in the twenties and thirties. In 1930 the section on hydrology was formed, and in 1940 the section on tectonophysics was set up. Hydrology is a broad subject in itself, and at present there are committees on stream dynamics, on snow, on glaciers, on underground water, and a subcommittee on land forms. Most if not all of these committees have only a relatively small representation of geologists; the majority are engineers or theoretical hydrologists.

New sections in the American Geophysical Union apparently grow out of committees, as interest in particular work increases. If this development continues, such subjects as the work of streams, the work of glaciers, and some aspects of physiography itself may become separate disciplines. Most of the workers in these new aspects of old subjects are not geologists; one may wonder how long geologists will complacently permit the invasion of their field in this manner. The writer knows of work now under way for a reference book on the physics of rivers, with respect not only to transportation of sediment but also to the development of stream-cut landscapes. Even the erosion cycle may vanish from geology!

Content of Specific Courses

If it is granted that the geologist needs more training in the basic sciences, it is also necessary that his training in geology should be integrated more closely with this requirement. Students commonly complain that their work in physics and chemistry seems to have no connection with geology, because so few of the principles they learn are ever mentioned in geology classes. This is not strictly true, because every teacher of geology pauses now and then to drive home a particular chemical or physical point. It is true, however, that most of the illustrations are rather elementary, and it is the rare teacher of geology who really gives his students an insight into the dynamics and energy relations of geological phenomena.

It seems to the writer that it is one of the responsibilities of the teacher of geology to acquaint himself with the content of the basic science courses, and to use as many principles as possible from them. Fundamentally geological processes are phenomena of physics and chemistry. The work of running water is essentially a hydrodynamic phenomenon. Anticlines and synclines are a response of rocks to forces applied to them, in terms of the elastic and plastic properties of the rocks. The erosion of headlands by shore agents involves the phenomena of wave refraction. In short, if the geology teacher uses specific physical and chemical principles to introduce his geological topics, and integrates them with the conventional geological discussion of earth phenomena, the student begins to see a set of fundamental relations beneath the welter of detail that constitutes an average course in geology.

Some teachers argue that beginning courses should emphasize the purely geological side of the story, such as the physiographic cycle, because it is inherently more interesting than a recitation of physical and chemical principles. That may be so, but the fact remains that the physical and chemical principles are there, and without them the student receives only part of the story. A more logical procedure, it seems to the writer, is to weave these principles into the geology courses at all levels, as the student's training both in geology and in the basic sciences proceeds. In this manner the student takes it for granted from his very first course that there is a natural relation between his geological training and his work in the basic sciences.*

By including a certain amount of integration throughout the student's first four years, he is prepared for the fifth-year courses on earth physics and chemistry mentioned in Table 1. It should be emphasized at the outset that these courses are not to be courses in so-called "geophysical prospecting" or "geochemical prospecting." On the contrary, the exploration aspects are merely by-products of a much more fundamental approach. The year's work in earth physics and earth chemistry should be a well integrated set of courses covering portions of the several disciplines shown in the lower part of Fig. 1. These disciplines should be woven together in terms of dynamics, chemical equilibria, and energy relations. Inasmuch as the student will have had fair preparation in the basic sciences by that time, plus some integration in his geology courses, the instructor may use his time to unify the entire subject. The scope of such a year's work may be indicated by the following "catalogue description":

Earth Science 301-2-3. A year's course in earth physics and earth chemistry. The earth's gravitational, electrical, magnetic, and thermal fields, and their unification by the theory of the potential. Properties of matter—elasticity, plasticity, etc. Force, work, and energy in earth problems. Chemistry of weathering, of mineral and rock genesis, unified by the principles of

* Hubbert[8] discusses the effects of integrating geology courses with the physical sciences, and raises the question whether such integration would frighten prospective students away from geology. He reaches the conclusion that in the long run a better quality of student will be attracted into the field.

chemical equilibrium. Applications of Le-Chatelier's Rule to earth problems. Energy relations of earth phenomena, unified by the laws of thermodynamics. In this year's work the student comes into contact with some aspects of all the geophysical and geochemical sciences, learns their scope, methods of work, and literature sources.*

During the year's work on geophysics and geochemistry, applications of the principles to prospecting may be brought out, thus placing the methodology in its proper relation to the principles. Such a series of courses will make the student aware of the explicit unity among the earth sciences, and will prepare him intelligently to keep abreast of current work in the geochemical and geophysical sciences. The new ideas the student acquires and applies to his later work will tend in large measure to offset the continued invasion of geology by other disciplines, with their tendency to withdraw the subject into their own special fields. The ability of geologists themselves to apply new physical and chemical principles to geology will tend to draw the several earth sciences closer together, because all workers will use a common language.

The point the writer wishes to make is this: as long as there is an increasing tendency for geological problems to be studied in the light of physical and chemical principles, why not train geologists themselves to make these applications, and thus place the geology departments in the forefront of such research, instead of in the rear?

Extensions of the Geology Curriculum

Comparatively little has been said thus far about the paleontologist. In the development of the basic curriculum, the writer was not concerned with specialization within geology. Because many schools emphasize the paleontologic and stratigraphic aspects of the science, however, it is necessary to consider this point. The writer believes that paleontology is an integral part of geology, and on the assumption that it will continue to be so, the question arises whether paleontologists should receive training different from that of the general geologist. Arguments can be advanced on both sides of the question. In the writer's opinion training in the physical sciences is as important for the paleontologist as for the geologist, but some cognizance must be taken of his need for training in the biological sciences.

One may return to the details of the work done by general geologists in an earlier section. To the extent that paleontologists perform tasks similar to these, the underlying training should be the same. If they perform different tasks, or additional tasks, training for those functions should be included in the curriculum. In general, it will be disadvantageous if two radically different curricula are developed, because that alone will tend to separate the physical and biological aspects of geology into distinct disciplines.

In the writer's opinion, a solution of the problem may be had by the development of four integrated curricula, leading to the degrees of Master of Science in physical geology, in paleontologic geology, in geophysics, and in geochemistry. Under such a plan, the physical geologist would follow the curriculum suggested in Table 1. The paleontologist would substitute basic training in biology for some of the advanced geology and basic science courses. The geophysicist would replace some geology and chemistry by advanced physics and mathematics. The geochemist would enlarge his chemical training at the expense of some advanced geology courses. The development of such curricula by the geology department through cooperation with related departments would place the geology department in a favorable position with respect to all earth sciences, because it would serve as the integrating factor in

* Hubbert[6] gives an outline of a year's course in geophysics. A somewhat similar outline is given by Beno Gutenberg.[7]

all four curricula. Moreover, students under each curriculum would have a common basis of training up to a certain level, and hence would feel themselves part of a unified field of science. The loss of some students by a stiffening of geological requirements would be more than offset by the influx of chemists and physicists into the earth science field, with its attendant advantages to the development both of the science and of the department.

The five-year curricula could be extended to a higher level, leading to degrees of Doctor of Philosophy in the four fields. Beyond the Master's level various specialized geophysical and geochemical courses could be offered, as well as additional training in geology, physics, chemistry, and mathematics.

Summary and Conclusions

This paper has attempted to show that within the several fields of geology itself there is an order of dependence. These fields, in turn, are dependent in some respects upon certain geophysical and geochemical disciplines, and the entire realm of the earth sciences is unified by fundamental principles of physics and chemistry. The training that professional geologists should receive was approached from these interrelationships. The net result of the analysis was expressed as a suggested curriculum that satisfies the conditions of preparing the general geologist for his tasks, and in addition equips him to cope with the ever increasing tendency toward a more physical and chemical approach—a dynamical approach—to geological problems.

There seems no escape from the conclusion that geology departments, with relatively few exceptions, have not given adequate attention to developments in the earth sciences during the last two decades at least. The exceptional departments have gone part way toward a solution of the problem of professional training for geologists, but the writer knows of none that has produced a rational plan to take into account the increasing pressure of the newer disciplines. One meets in every branch of applied geology men who entered the field not by means of geological training, but as physicists, chemists, or engineers. This influx is wholesome for geology, but it is regrettable that geology departments apparently took so little cognizance of the need in their own field for men trained in the basic sciences.

It would be advantageous not only to geology departments themselves, but to the newer disciplines of geophysics and geochemistry as well, if geology departments made a greater effort to cooperate actively in their continued development. This could be done by setting up parallel curricula of the type mentioned. In addition, room could be provided in the geology department for specific courses in those disciplines not yet established in university organizations. As a start, specific courses could be offered at an advanced graduate level by specialists in the fields, and as unification proceeded men trained in the department would be able to carry on the work over a wider range of subjects, and might be absorbed into the staffs of smaller institutions. A program such as this would train earth scientists in the broadest sense of the word: men who could go directly to the field for their evidence but who need not hesitate to interpret that evidence in the light of fundamental physical and chemical principles.

References

1. T. C. Chamberlin and R. D. Salisbury: Geology, 1. New York, 1904.
2. Emmons, Thiel, Stauffer and Allison: Geology, 1. New York, 1939.
3. M. K. Hubbert: The Place of Geophysics in a Department of Geology. *Trans.* A.I.M.E. (1940) 138, 34.
4. W. Lindgren: Economic Geology as a Profession. *Econ. Geol.* (1919) 14, 79–86.
5. W. Lindgren: The Education of the Geologist. *Econ. Geol.* (1923) 18, 405–409.
6. R. W. Brock: The Education of a Geologist. *Econ. Geol.* (1923) 18, 595–597.
7. B. Gutenberg: Geophysics as a Science. *Geophysics* (1937) 2, 185–187.

The Education of an Exploration Geophysicist

By M. M. Slotnick*

(New York Meeting, February 1941)

It was once aptly said that a sign of approaching senility is ceasing work on a subject and beginning to talk about it. Perhaps that explains why, after many years in which part of my duties has been the training of college men in various branches of petroleum exploration geophysics, I have now begun to talk about it.

In making an outline of what I believe ought to be discussed under the general heading of the title, I found it almost impossible to subdivide the ideas into an ordered set of discrete subjects. Rather, the pertinent remarks seemed to interlock almost everywhere. The consequence is that it will be necessary to start with the conclusions and then try to justify them by jumping back and forth.

However, based on the types of men with whom I have had to deal, the subject naturally divides itself into two parts. In the first part, I should like to deal with the case of those undergraduates whose natural bent is toward the physical sciences and who may decide to enter the geophysical fold as a career. The other part will deal with those many men, geologists and engineers for the most part, who have drifted into exploration geophysics by one means or another, and whom it is necessary to train for geophysical work while they are occupied in their routine jobs. Here it may be in point to remark that most men in exploration geophysics at present have been developed from precisely the latter group, and that the problem of training here is of great importance even though, in this paper, it will perforce occupy the secondary place.

Training of a Geophysicist

The outstanding reason for the perplexing problem on the training of a geophysicist is that ideas differ on the answer to the question: "What is a geophysicist?" In any of the scientific "specialties," like physics, for example, it is relatively simple to pigeonhole a man as being qualified to call himself a physicist. That appellation applied to an individual does not mean that he has mastered only the branches of intellectual endeavor usually associated under the broad name of "physics." We expect him also to have a more than mere acquaintance with mathematics and chemistry and some understanding of most of the other sciences. But note this important point—we expect our physicist, whom we have chosen as an example, to be intelligently trained so that, if necessary, he can and will know how and where he can get the proper information on a subject in which he is not a specialist; he will know how to absorb that information and turn it to his uses.

It seems to me that this is the outstanding characteristic of a man who can truly call himself a scientist: that he is a specialist in one of the broad branches of science and that he has enough training and discipline in the scientific approach so that, when called upon to do so, he can intelligently absorb knowledge from another bordering science (and all sciences not only border upon one another to some extent, but more often, overlap one another), and

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apply it to his work when such application is indicated.

The crux of the answer lies in this last paragraph. The very nature of geophysics demands broadness of scientific training rather than intensive training in only one of the classical branches of science. True, he may be fundamentally a physicist, chemist, mathematician or geologist insofar as his formal training is concerned; but he must have more than a passing acquaintance with the scientific methods and thoughts of all the others—an acquaintance, in fact, such that he can prosecute intensively any problem in those other fields that presents itself, in an intelligent, authoritative fashion.

The indispensable subjects for the qualified geophysicist are, first of all, physics, mathematics and geology—in the order named—and a solid foundation in the classical structures of those sciences, particularly in the first two. With these tools in his kit, he can master, if necessary, any of the various specialized problems that may come up. Moreover, any undergraduate well prepared by his education in the basic courses of these sciences can be converted to geophysics without any undue extra effort.

The man I envision as truly a geophysicist is not one who can necessarily "troubleshoot" amplifiers, operate a magnetometer or replace a torsion wire in a torsion balance. Such matters as these he can learn very quickly and easily if the occasion arises, without trouble and in very short order. A geophysicist, in my sense, is one who knows the theory of the geophysical methods, the whys and wherefores of the operations, the meaning and necessity of the corrections, computations, the significance and limitations of the data, and something of the geologic implications of his final map. These are of prime importance in characterizing a geophysicist. It is thus my contention that it is not necessary for a man to decide early in life to pursue a geophysical career. The topics necessary for such a career are precisely those a young man will need in order to be well grounded as a physical scientist.

I had hoped, in preparing this paper, to review and reread the other papers of former years that bear on this subject. It occurred to me, however, that it will be better to write this independently and then, perhaps, compare these conclusions with those previously arrived at—even though this entails the risk of possible repetition.

It is now time to be more specific and detailed in describing our geophysicist, in order to arrive at a clearer picture of what the preceding conclusions imply.

Minimum in Physics

What are the minimum demands in physics that must be expected of a geophysicist? It is almost trite to point out that we must expect ability to handle problems and experiments in heat, sound, light, electricity and mechanics. This means a solid understanding of theory; and that, in turn, means a usable, practical and real understanding of the methods of the calculus, of differential equations and other mathematical topics of that level of advancement. If, to such a preparation, is added a good basis in geology, and also if, at the same time, other scientific courses and cultural subjects are pursued as minors, particularly chemistry and English courses, what more do we need to turn out a good geophysicist?

Surely, a man so trained can grasp the necessary theory of geophysical methods, of geophysical instruments and of geophysical interpretations with no great difficulty.

Mathematics

In the mathematical requirements beyond the first courses in trigonometry and analytic geometry, one topic that is very often neglected but that is indeed a necessity is three-dimensional analytic geometry.

Since spatial conceptions and relations are always used in geological investigations, the ability to handle the analytic relations that solve the necessary problems easily is of very practical importance. It seems to me that this requirement and that of descriptive geometry too should be recognized in formulating the geologic curriculum.

In the undergraduate years, a broad and well-balanced series of courses in the calculus—differential and integral, of course—must be pursued. If at all possible, the first course, at least, in differential equations and the beginnings of advanced analysis should be included. These courses should be given with due attention to rigor. The solution of numerical problems should be taught as a consequence of the theoretical work rather than as the course itself. In the numerical solutions of the problems, too, yeoman service can be done in teaching the art of numerical approximation methods and the theory of errors.

Geology

Beyond the courses in general geology and structural geology in the undergraduate years, there is probably too little time left for further work, except to include a summer of field geology. The intelligent undergraduate, however, in this amount of work has a fairly complete background upon which he can be inducted into geophysical work.

Graduate Work

A year, or preferably two years, of graduate work can well be added with a good deal of profit. In these graduate years, advanced work in mathematics, physics and geology can be pursued and some of the time can be devoted to the practical problems of geophysics. Here, for the first time, I mention actual work in geophysics.

It is only with all this preparation that the young man can pick up, let us say, any one of the recent books on exploration geophysics and read it understandingly and profitably, without grasping at things beyond his reach. He is capable of learning the field methods and techniques very readily and he is, at the same time, in a very good position to consider whether he is interested in a geophysical career, and whether, too, he feels ambitious to go on to the doctorate in a specialized branch of geophysics.

The ideas I have thus far broached are perhaps on the conservative side, when weighed in the balance used by our neo-educators, but I feel convinced that they are on the right track. My feelings in education are quite strong on the necessity of teaching the fundamentals of science and in the discipline of scientific thinking and rigor. The "trimmings" of specialized career subjects can always be absorbed by an intelligent man well trained in the fundamentals.

A colleague of mine once put the idea rather aptly, albeit somewhat too strenuously, by saying that, in his opinion, all engineering courses and schools should be abolished. Certainly, if an engineering education consists essentially of learning how to use the trade handbooks, that stand is well taken. Indeed, any well-trained mathematical physicist can turn his attention readily enough to any engineering problem, solve it and even go on farther from there. Or, to put it in a different way, the outstanding, top-rank engineers in any field are certainly not just "engineers."

The group of geophysicists as I envision them will fall into the class of those most unfortunately once called "physicist-geophysicists," in contrast to another group called "geologist-geophysicists." If the latter term means anything, it is to call attention to the large number of men who have been raised purely as geologists but who have had to turn their attentions to geophysical activity in their jobs. There are many such men, and, unless their work

is merely routine many unfortunate circumstances follow.

Geologists in Geophysical Work

Let us now turn our attention to the young men, "pure" geologists by training, who are being used in exploration geophysics in various capacities; for instance, the many young men who serve as routine computers in reflection seismograph crews. These young men, as a group, do excellent work as long as the details of transcribing the reflection travel times from the records to the sections and maps in terms of depths and contours—that is, tables, charts, formulas—are all handed to them and explained carefully. If, however, for one reason or another, these charts are changed, the formulas revised, the setups altered, someone must explain the new procedure in detail. The young men are not qualified to work out the necessary trigonometry, simple as it is, or the suitable geometry—and come to their own conclusions. They have not been trained to think in terms of measurements.

For many years it has devolved upon me to teach such geologically trained people the various mathematical and physical concepts underlying the routine observations being made from day to day in the field and translated to the maps. On the whole, the results have not been too encouraging—for one reason only. The men have had good training evidently in geology, but have learned no other scientific discipline. As a result, the physical concepts of mensuration, the significance of data and the mathematical approach is completely out of their ken. Even in the surveying which they have done in the school work, there is a lack of full appreciation of the trigonometry behind the tables in their handbooks.

It is very unfortunate that the mathematics so sorely needed for geophysics is so much more difficult to master in the post-school years than it is in the formative undergraduate years—but that is the outstanding need for the geologist, as he is brought up at the present time, if he is to be converted to geophysics after his school years.

To me the conclusion is inescapable that geologists must be prepared in mathematics and physics; in the former, at least through the calculus and in the latter at least a good foundation in general physics, which probably means two years work. To this must also be added a good course or two in chemistry. I cannot be more specific than that—but there is no need to be so. A man so prepared can learn very rapidly a good deal about exploration geophysics without undue expenditure of time and money.

Conclusions

It is my earnest desire that I should not be misunderstood on the stand I am taking. I realize that I have generalized to some extent and so the conclusions are to be considered in that light. No one who has watched a geologist on the job can fail to have respect for what can be done by "purely" geological methods. It may have been noted, however, that even in many cases where geology has been most useful there was an intuitive use of mathematical-physical concepts, which could have been more definitive. On the other hand, too, there are very often cases of "overusing" these mathematical-physical concepts—of "overcomputing," so to speak, the results of the measurements to absurd conclusions. These are some of the things that can be minimized by proper training.

The conclusions that I seek to draw, then, are, after all, rather simple and not too arbitrary. Whether the young man wants to enter geophysics or geology as a career, he should first realize that he must have a broad, balanced preparation. His work in geology should not be narrowed down into the channels that are in "pure" geology. He must prepare, both for scientific discipline and for the sake of having

scientific tools, in the quantitative methods of science. He must know his geometry and calculus, not only for the purpose of using them as tools but also for the sake of developing his thinking powers to draw conclusions. Too often, otherwise, some psuedoconclusions are given him, which he takes on faith because his critical powers are subordinated to the idea that "it must be so because it is in the book." What "forces" are and what they can and cannot do must be learned, not just mimicked, and they are learned in physics and other quantitative sciences.

The Nature of Geological Inquiry and the Training Required for It

By Walter H. Bucher*

(New York Meeting, February 1941)

This symposium is designed to lay the basis for a general discussion of the place of geophysics in the training of geologists. As there is danger that in the ensuing debate individual interests may be given emphasis out of proportion to their place, we shall do well to view the whole field of geological inquiry in order to see the problem in true perspective.

The Nature of Geological Inquiry

"Basic" and "Complex" Sciences

It is convenient to divide all science into two major divisions, the basic and the complex sciences. The basic sciences separate out from reality such entities as "substances" and "movements," describe their behavior in terms of arbitrary units of measurement and derive from them by progressive abstractions concepts and patterns of behavior that exist between them, so-called general "laws" and "properties" of nature.

The complex sciences, on the other hand, deal, with little or no abstraction, with those objects of reality that are accessible to man in the atmosphere, the hydrosphere, the lithosphere and the biosphere.† Their work comprises two types of inquiry. One is concerned with abstractions to the extent of dealing with types rather than individuals—that is, with such things as plants, animals, protoplasm; clouds, streams, glaciers; volcanoes and mountain ranges. It comprises the search for general properties and patterns of behavior or "laws" that characterize the objects and their reactions to each other. These properties and laws apply always, everywhere. They are independent of the stream of time. We may call the results of this sort of inquiry *timeless knowledge.*

The other type of inquiry is concerned with the objects themselves—that is, with this animal and that plant; this river system and that mountain chain; this glacier and that valley. Like all concrete objects in nature, they are subject to change with the passage of time, especially when it is measured in years, centuries, eons. The characteristics by which we recognize them —indeed, their very existence—are dependent on their position at this point in the stream of time. This we may call *time-bound knowledge.*

The so-called descriptive sciences are all bound to the past of which the objects of their study are the product and through which alone their present properties can be understood. They are *historical sciences.* This obvious fact is easily overlooked, which leads to serious misunderstanding, as we shall see later.

Dynamic Geology

With this broad picture in mind, let us now examine the nature of geological inquiry, defining, for the purposes of this discussion, geology as the science of rocks. Air is not a rock; water is. Meteorology and climatology are, correspondingly, gen-

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† In contrast with astronomy, which occupies a unique position.

erally placed separately for administrative purposes, while oceanography and hydrography tend to be grouped with geology, as witness the Coast and Geodetic Survey and the Geological Survey of the United States.

In this field of geological inquiry, then, we distinguish first the search for timeless knowledge, the study of geological processes. This is widely spoken of as "dynamic geology." We do not have to be told that there are no "geological" processes coordinate with and independent of the processes of physics and chemistry, nor are we so naive as to assume that "dynamic geology" is merely the sum of "geophysics" and "geochemistry." We know that, as phenomena observed at the complex level of unabstracted reality, the geological processes will ultimately be (and are in part now) understood in terms of the basic sciences; that is, as expressions of the interplay of specific laws and properties of physics and chemistry. But that does not relieve us of the necessity of finding out what the geological processes are and of calling them by a distinctive name.

The distinguishing feature of the processes that we call "geological" is that their dimensions in space and time vastly exceed all laboratory experience. When a block of ice breaks off the front of Hubbard glacier, its fall is not called a "geological" process; but the movement of the whole glacier is. The wavelet that plays on the sand may be studied directly in an experimental tank, but not the seismic sea-wave. This is what they forget who are too quick to identify "geophysics" with "dynamic geology." The typical "geological" processes can not be studied directly by laboratory methods but only indirectly by their results; that is, by the methods of the historical sciences, which are foreign and in a large measure distasteful to the physicist. These methods involve observation and description, analysis by comparison and not by mathematical treatment. Let us look at a few examples.

1. Near the end of the last century, Glenn Culbertson drove metal spikes into the rock above the falls of Clifty Creek, near Madison, Ind., and used them to survey accurately the front of the falls. A number of years later, he surveyed it again. From the observed recession of the shale face of the falls and the length of the gorge below he computed the time that had elapsed since the falls came into existence.

This was a typical application of simple physical methods to a geological problem, but the figure he obtained was of a different order of magnitude from that to be expected from similar observations at Niagara Falls and elsewhere. Something seemed wrong. A geophysicist could see many reasons for the discrepancy, but probably he would not have thought of the chief one and he certainly could not have proved it by any of his methods. For the discrepancy is due primarily to the circumstance that the gorge below Clifty Falls came into existence before or early in the Illinoian glacial epoch, while that below Niagara Falls started during the late Wisconsin epoch. The tireless work of dozens of astute field observers was needed to prove the multiplicity of glacial epochs during the Ice Age. Those observers walked or rode on horseback and buckboards over the plains and hills of the northern United States and Europe and in the glaciated valleys of the Alps during several decades, observing and comparing topographic forms and surface deposits, plotting their distribution on maps and measuring elevations. There is no other road to such knowledge.

2. Geophysicists have devoted much thought to the nature of the still active forces that have caused the progressive emergence of Fennoscandia and of northern North America. But the extraordinarily complete and quantitative information that is available for such thought concerning Fennoscandia had to be collected by the geologist. For North America, most of this

task still lies ahead of us, with weary treks through the bitter wastes of the crucial country that surrounds Hudson Bay. Geological processes are very real things that must be studied largely by direct observation. To recognize and appraise correctly the significant topographic features that betray movements of the earth's surface and to distinguish them from others that simulate them requires methods of observation and skills of judgment that are the essence of geological work.

3. The great granite plutones that have come into existence near the axis of every growing welt of folded mountain may be the end products of magmatic differentiation intruded as liquids into the crust from great depths, or they may be the result of impregnation and replacement, softening and partial melting of the rocks of the outer crust. Here is a major geologic process, recognized as typical of crustal deformation in all parts of the globe. Here, as in all such cases, physics and chemistry can tell only the possibilities. The geologist must find out what the process really is. He needs strong legs, tireless energy and trained eyes above all else. He must go and see. No one else will do that for him.

All Other Geology

So much for geological processes. By force of circumstances, the greater part of all geological work is not primarily concerned with "timeless" knowledge but with concrete, "time-bound" reality. It deals not with ore bodies, but with this ore body; not with valleys in general, but with that valley. The mining engineer wants to know "What ore? How much? How deep? Where?" in this body. The civil engineer asks "At what depth bedrock? What kind? How strong?" in that valley. The paleontologist, tracing one strand in the mysterious tangle of organic evolution, inquires "How old is this layer?" "In what environment was it formed?" "How quickly did it form?" The answers to all such questions, in so far as they can be given today, are found through field observations and through reasoning along lines of tested theory that demand much judgment born of experience, and lie in part completely outside the field of thought of the physicist and chemist.

The modern geologist employs, besides his own eyes and brain, the skills of the specialized geobiologist (paleontologist), geophysicist, and geochemist. In order to evaluate their findings properly, he must speak their language as far as possible—but his task is too large to permit him to try to acquire their skills.

It must be remembered that while geology, like every one of the complex sciences, is "dependent" on the basic sciences for the ultimate "understanding" of its empirical findings, it is master in its own field of observation. It is "dependent" only as a sovereign depends on the advice of the experts whose special knowledge he needs to grasp the meaning of the complexities of the realm that it is his task to control.

What disturbs his fellow workers in basic sciences most is the geologist's infrequent use of mathematics as a tool. The distrust that results springs from a lack of comprehension of the difference between laboratory and historical science.

To illustrate: It requires a great deal of ballistic—i.e., mathematical and physical knowledge and computing—to create a gun that will place a shell precisely at a given point a long distance away. This is a case of a laboratory science applied to human purposes. Compare this with an example of historical science similarly applied, that of an investigator who sets out to determine whether a certain shell was fired from a certain gun. He will hardly ever have recourse to figuring. He will scrutinize the shell for such telltale marks as every barrel impresses on a shell, which establish uniquely the identity of the barrel from which the shell was fired. An investi-

gator in the descriptive or historical sciences seldom uses mathematical methods—not because he is incompetent or inert, but because he can achieve his object with greater certainty and faster without them.

For an example from the field of geological processes, take the question concerning the nature of glacier movement. Does Bernouilli's law apply to the movement of ice in a glacier? The theory of solid flow probably is not far enough advanced to tell confidently. At any rate, the geologist, being a true scientist, wants to know whether it does actually apply. He climbs the rock ledges below glaciers in the Rockies and on hands and knees searches the polished surfaces on the vertical walls of the ledges for marks that show whether the ice moved eddywise or not. This Max Demorest did, and thereby demonstrated a fact of great importance to the physics of solid flow.

Training Required

Having thus outlined the essential nature of geological inquiry, we are ready to ask what training is needed for it. Let us list first the training that all geologists must secure:

1. First, and above all else, the future geologist must learn to observe in the field and to record his findings adequately. The training to observe accurately and intelligently extends to the use of simple instruments, such as compass, clinometer, alidade, topographic map and aerial photographs used stereoscopically, camera, hand lens, microscope.

2. Next he must acquire ready familiarity with the terminology and criteria that distinguish the important kinds of minerals, rocks, fossils, textures, structures and surface forms.

3. Then he must know thoroughly the empirical properties of the essential geologic processes, with as much reference to their meaning in terms of physics and chemistry, zoology and botany, ecology and climatology, as time permits.

4. He must learn to use the logical methods of the historical sciences: how to compare relevant facts incessantly, how to weigh evidence, how to avoid the many logical pitfalls.

5. And finally, he must become familiar with the literature and the shortcuts to its use.

To these must be added the following items from the fields of the physical sciences for all men who expect to work in any phase of physical geology whatever (i.e., surface and ground water; geomorphology; regional and structural geology; volcanology):

6. As much familiarity as possible with those fields of physical science from which the understanding of geological processes must come (i.e., hydrology, industrial rheology and physics of materials in general; physical chemistry of solutions and melts).

7. Sufficient familiarity with the principles underlying the use of the modern geophysical instruments to make possible their intelligent application to geological investigations.

Place of Geophysics in Training of Geologist

The last two items define the place of geophysics in the curriculum of the future geologist, as the writer sees it. It accommodates only a part of geophysics, and that only in outline. This is merely the expression of the fact that the work of geophysics is at present and always will be done by two groups of men, the geologically informed physicists and the physically informed geologists.

The latter are men with thorough geological training who have learned to speak the language of mathematical physics sufficiently to avail themselves of the laboratory investigations in many fields and apply them to a more adequate understanding of geological processes and transmit that

better understanding in precise language to the coming generation of geologists.

The former command the high-powered tools of modern mathematics and a thorough knowledge of modern physical instruments, especially in the electrical field. They are physicists who have become sufficiently fascinated by the geological aspects of physical processes to turn away from the remunerative field of basic industrial and engineering science to experimentation and mathematical analysis in the interest of geological knowledge.

The incentive to turn to geological problems must come, for both types of men, from the geology departments in the universities. This is an added reason for the introduction into the modern department of geology of a course in advanced dynamic geology in which the results and the precise mathematical language of the basic sciences are applied to a better understanding of geological processes. For young men who have grown into mental maturity in an atmosphere of mathematically formulated thinking are not apt to become enthused over geological problems in the purely descriptive courses on dynamic geology, which in most institutions are the only ones offered (generally to freshmen!).

The introduction of such an advanced course in dynamic geology is thus a necessity for the opening up of the field of physical geology to the physicist, as well as for the maturing of the future geologist. Such a course should be given by a physically trained geologist.

For the time being, the physically trained geologist who is sufficiently broad-gauged to be able to offer such a course is a gift of the gods. We must recognize his value and go out of our way to secure his services. Not until we have provided him and his course can we and must we demand a minimum of preparation in mathematics and physics for all students who expect to work in any field of physical geology. This minimum should consist of elementary mathematics, including differential and integral calculus, and a general physics course that has the calculus as prerequisite. To demand this minimum in a department in which the student never goes far enough to see an integral is just as futile as to demand a reading knowledge of German in a curriculum in which no reference is ever made to the German literature.

As was said above, we must rely on such a broad-gauged advanced course in dynamic geology to draw and win over young physicists into the border fields between physics and geology, such as tectonophysics or hydrology. Now and then an exceptional young geologist with a good physical-mathematical background may turn into this field; but it would be folly for a department of geology to set out to deflect the interests of young undergraduates from the start in the direction of mathematics and physics, in the hope of "forcing" a crop of geologically trained physicists. It would be folly for two reasons:

1. Men go into the so-called basic sciences because they are drawn, consciously or subconsciously, toward abstractions by what might be called a philosophic turn of mind. (If that phrase offends you, let me remind you that a generation that had a better perspective than ours over the whole range of activities of the human mind spoke of physics and chemistry as "natural philosophy.") When capable men go into the so-called descriptive sciences, they do so not because of a weaker intellect, but because they are drawn by a love of tangible things. They start by collecting beetles, plants, minerals, topographic maps. Albert Heim was a lithographer's apprentice and drew Alpine panoramas with an old camera lucida. He loved the mountains, and his curiosity was aroused by their shapes. Curiosity and the love of tangible reality is a precious asset in young students of geology, which must be preserved. They will be called upon to live for months and years away from com-

fort and the companionship of their kind. We must not force the boys whose love and curiosity have been aroused by minerals and fossils into a curriculum so dominated by mathematical, physical and chemical subjects that they are kept largely from the objects that are integral parts of the study they have chosen as their life work. Let them acquire basic and quantitative knowledge *pari passu* with descriptive studies in mineralogy, petrography, zoology, and paleontology.

2. We must not try to turn young geologists into physicists, above all because most of the groundwork in the laboratory phases of geophysics will be done ultimately by others—the pressure of industrial needs will see to that—but the task of geological fact-finding will be done only by geologists.

The only other provision that was made in the outline above for geophysical instruction in the training of a future geologist concerns a general introduction to the modern methods of geological exploration by means of geophysical instruments. The writer is convinced that great danger and futile loss of time result from attempts to turn geologists into men competent to handle the modern geophysical instruments. Nowhere in the whole field of science is a little knowledge a more dangerous thing than in geophysical methods of geological exploration.

On the physical side, evaluation of the instrumental results involves complete insight into the limitations of the method and the possibilities of instrumental errors. On the geological side, it requires a wide perspective in the fields of stratigraphy, paleogeography, and structure. That is why, in a similar symposium three years ago, Donald Barton pointed out sharply that the mere teaming of a geologist and a physicist can not lead to usable results in geophysical investigations with such instruments as the torsion balance or a modern seismic outfit.[1] The ideal would be a single investigator who is as competent a geologist as he is a mathematical physicist and instrument technician. But to produce such a combination requires either such exceptional ability or such length of time that we cannot build a curriculum on it. The team that brings results is one consisting of a physically trained geologist and a geologically trained physicist. These are the same two types that we have visualized before. The training of the one rests in the hands of the geology department, that of the other in the department of physics, both preferably in a competent engineering school. The essential point is that the physical geologist in this team be above all a thoroughly trained geologist and his teammate a competent theoretical physicist, yet each sufficiently familiar with the field of the other to understand the other's language.

For the basic training of the two types of men, there is no specific need of any course in the details of the techniques of geophysical exploration. No more is needed than a relatively short, broad course, such as that suggested in the outline above. Such a course can be given by a physically trained geologist, but that institution will place the crowning stone on its educational structure in both lines which has the wisdom to add either to the department of geology or to that of physics a master in geophysical exploration who will give this general course. He will have graduate students who are apprentices under him. Their specialized training will communicate to the nonspecialized students in the related departments a concrete understanding of the nature of the work. Their example will do more than anything else to stimulate a growing demand for more and more precise knowledge in all parts of physical geology.

[1] *Trans.* A.I.M.E. (1940) 136, 74.

The Place of Observational Geology, Past and Present

By Benjamin L. Miller,* Member A.I.M.E.

(New York Meeting, February 1941)

The essential differences expressed by the different speakers participating in this symposium concern merely the relative emphasis placed on the subjects that are commonly included under the term "geophysics" and the branches of science that form the basis for investigations in this field.

In order to appreciate the present situation it may be profitable to briefly refer to a few historical matters. One can find almost countless descriptions of geological phenomena long antedating the introduction of the title of "geology," which has been credited to Richard de Bury in the fourteenth century. Interpretations, when they were offered, were generally pure speculation. Only toward the close of the eighteenth century do we find theories developed as the result of observations and tested by additional observations.

It is difficult to select and give proper credit to the individual who was particularly responsible for turning geology into a distinctly observational science. William Smith, who has been called the "Father of English Geology," certainly represents the period when observation was the only method used. As he traveled through the British Isles, "sometimes 10,000 miles in a year," he was continually making notes of his observations. Geikie says: "His plain, solid, matter of fact intellect never branched into theory or speculation, but occupied itself wholly in the observation of facts." William Smith, with others of his time, definitely laid firmly the foundations on which modern geology has been built. Field and laboratory observations can no longer be said to constitute the sole basis for geologic contributions but we have not laid aside the methods of Smith and his followers. It is folly to underestimate the fundamental value of the observational part of geology in the present.

The objection to purely observational geology is that it is mainly qualitative and not quantitative, general and not specific. No one can deny this charge and probably there are few who do not welcome every method or process whereby we can put aside generalities for definite established values. Physics is the science that has particularly come to the aid of the geologist in this respect.

Contributions of Physics

It is not the intent of the writer to enumerate or to evaluate all of the contributions to geologic advance in the field of physics. A few only are used for the purpose of illustration.

When Clarence King, Director of the United States Geological Exploration of the Fortieth Parallel, invited Ferdinand Zirkel to study 2500 thin sections of rocks collected from the western United States, the use of the microscope came into general use. Zirkel's report was published in 1876. He was not the first to use transmitted light for microscopic rock determination, some work having been done by Henry Clifton Sorby and others some years earlier, but he was the first to put into general use this method. We may well claim that this

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introduction of optical methods was the first major contribution of physics to geology and the beginning of geophysics, although the latter term itself appeared in print as early as 1853.[1]

From that time to the present one physical principle after another has come into use to supplement the purely observational method in our geological investigations. The dip needle, long known, and the magnetometer for the location of iron-ore deposits were early used. Season after season the geologists with compass men systematically paced through the forests and swamps of northern Michigan in search of hidden deposits of iron ore.

The great spurt in the application of physical methods came shortly after the close of the World War in 1918. The writer's introduction began with Sherwin F. Kelly's demonstrations of the spontaneous polarization method. The electrical method was followed by the seismic and gravity methods. Since our field of work has long attracted all kinds of divining manipulators, it was only natural that many geologists for a time looked askance at the new offerings and were extremely skeptical as to their scientific value. The oil operators were the first to wholeheartedly accept the new methods, and to them the rapid advance in the use and in the improvements of the various methods is mainly due. Geophysics has now become firmly established as a useful adjunct to the purely observational method, and all branches have benefited, but especially structural and economic geology. Structural sections based on surface exposures have been checked and modified and in many regions completely hidden structures have been accurately determined.

Geology Not Supplanted

As would be expected, the great amount of attention directed to geophysics has led some enthusiasts to overestimate its importance and to minimize the value of the earlier observational methods. Therefore it seems to me that a few of the men trained in the older school have been given a place on this program for the sole purpose of applying the brakes to some of the extravagant claims.

With the fullest appreciation of the value of geophysics, it is still maintained that the physical data furnished in ever increasing volume are supplementary to observational geology. Many of the most important problems confronting the geologist in stratigraphic and economic geology do not lend themselves to geophysical measurements. Stratigraphic breaks and unconformities of profound significance may yield no geophysical evidence of their existence. Varying chemical changes in rocks may not be revealed by any physical data. Countless examples of these limitations might be cited in addition to those given by previous speakers. The writer mentions only one illustration from his special field of investigations. Limestones and limestone products are widely used in almost every field of industry. They vary widely in both chemical and physical properties and the adaptability for specific uses depend upon these properties. A variation of a few per cent of magnesium carbonate renders the stone useful or useless in the manufacture of Portland cement; a variation of a few per cent of silica renders it desirable or undesirable for fluxing purposes; and similar variations of aluminum and iron constituents also render the limestone fit or unfit for definite uses. No known physical method can furnish the requisite information; direct observation is essential.

Observational geology, which at one time constituted virtually the whole field of geology, has not been replaced by geophysics—merely assisted. It may well be asserted that the observations of the geologist are necessary for the formulation

[1] S. F. Kelly: A Perspective of Geophysics. *Trans.* A.I.M.E. (1940) 138, 32.

of most of the geologic problems and they still form the basis for the interpretation of the data of the geophysicist. Many examples in support of this claim might be cited.

Geophysics in College Curricula

Admitting the value of the various methods of investigation that the physicists have brought to the attention of geologists, due consideration must be given to them in our college curricula. Surely college teachers are not doing their duty unless they include courses for the geological students that will familiarize them with the new tools. At this point a real problem appears. The writer has long been a member of a university faculty and has participated in numerous revisions of curricula. Indeed, curricula revision seems to be omnipresent in almost every college and university. At the outset general agreement of principles is apt to be obtained by all the faculty responsible for the revision but when it comes to the inclusion of particular subjects there is bound to be disagreement. So many compromises must be made that seldom is any department fully satisfied with the outcome. The limitations of a four-year course, which is the rule in almost all our educational institutions, become serious in all revisions. An almost universal plea in recent years is that more courses be required in English, economics, history, foreign languages and other nontechnical and nonscientific subjects. How then can place be made for the additional courses in mathematics and physics considered necessary by the geophysicist? Some believe that additional mathematics and physics and the application to geological problems must be forced into the graduate school, not by choice but by necessity. The five-year undergraduate curriculum as an alternative is frequently advocated but is still decidedly unpopular.

Another phase of our student training that must be considered is the existing division of geology into many branches. The general geologist of the past, who covered the whole field of geology, is no more. Geologists have become specialists. Perhaps they have gone too far in specialization. The "soft-rock" geologist may even scorn the investigations of the "hard-rock" geologist, and vice versa. Some of our most able geologists, judged by their contributions, profess almost complete lack of ability in the exact sciences of mathematics and physics. There is a feeling in some quarters that students who lack this aptitude should be discouraged from entering the field of geology as a life work. The writer does not share that point of view.

Where the staff of the department of geology is sufficiently large to permit a variety of offerings, plainly there is an obligation to steer the geological student into the branch for which he is best fitted. As far as the curriculum will permit, the mathematically inclined student should be encouraged to make all possible preparation for the promising field of geophysical work, but not at the expense of the more fundamental parts of geology. On the other hand, there is a place for the student of geology whose inclinations run in other channels.

Geochemistry

This symposium is concerned mainly with geophysics, but we should not overlook the important place of geochemistry, which has proved so valuable to geology. Many of the significant advances in the study of ore deposits are due mainly to the geochemists. Repeatedly it becomes necessary for the economic geologist to consult his chemical associates, and generally the specialists in the particular branches of chemistry. For example, the importance of colloids in mineral deposition and mineral alterations is readily recognized. So rapidly has that branch of chemistry developed that it is the colloid

chemist alone who can give the necessary assistance. It may well be that in the coming years the geochemist may find as distinct and fertile a field as the geophysicist in the study of earth phenomena.

Geologists Willing to Cooperate

A belief in the shrinking importance of the geologist in the study of the earth and its constitution has been intimated, if not definitely expressed. The physicist and the chemist are given credit for most of the important recent advances in geology. Even if such a charge were true, this should not be regarded as derogatory to geologists. Geologists generally do not intend to exclude the other scientists who may make the earth the object of their investigations. On the contrary, most geologists should and do welcome all investigations of allied scientists and gladly share with them their accumulated knowledge. Instead of being jealous of encroachment in the sphere of earth studies, geologists should invite the trained physicist and chemist to undertake investigations into these border fields of the earth sciences. Plainly, many of the problems of the geologist demand the assistance of the specialist in these allied sciences. The more complete such cooperation becomes, the more valuable will be the results.

Physics and chemistry alone have been mentioned. The writer does not wish to convey the impression that they are the only sciences that can assist the geologist. Astronomy, biology and meteorology have their place in the study of the earth problems. Facetiously, we might even suggest that specialists in logic and psychology be invited to come to the assistance of the theoretical geologist.

A few days ago the writer came across a volume published 99 years ago, which is of interest because it contains statements very similar to some of our present contentions —"Practical Geology and Mineralogy," by Joshua Trimmer (Philadelphia, 1842). The following quotation is from that old book:

> . . . It is by no means intended to deny the dependence of geology on the other sciences; on the contrary, it is admitted that he who would be a perfectly accomplished geologist, ought to be familiar with the whole circle of them. He ought to be thoroughly versed in mathematics and general physics, in order that he may know what are, and what are not sound data on which to found his inferences—he ought to be skilled in mineralogy, that he may know the proximate constituents of rocks. Of the general results of chemistry he must not be ignorant, and he will find it a great advantage to be expert in chemical analysis. The organic remains entombed in the strata, will make constant demands upon him for a knowledge of zoology in all its branches . . . The geologist ought moreover to be a botanist of the highest order, and in the most extensive sense of the term. He ought to be able not merely to refer a plant to its place in some artificial system, by counting its stamina,—a process which he will rarely, if ever, have an opportunity of applying to the fossil vegetation of former worlds,—he ought to be able, from the examination of a stem, a leaf, or a seed-vessel, to determine the natural group to which the plant belongs, and by pointing out its habits, to throw light on the circumstances under which the stratum containing it was deposited. He ought, moreover, to be a good draughtsman, and a skilful practical surveyor.
>
> Acquirements so varied and extensive as these are attainable by few, and yet much may be done in geology with a very limited proficiency in these branches of knowledge. Without a very profound acquaintance with any of them, we may master all the facts of the science, and all the inferences deducible from them, and what is more, we may be qualified to institute active original research, and to enroll our names on the list of those who have added, by their discoveries to the sum of human knowledge,—for geology is a science of observation.

This symposium has shown the value of the rapidly expanding branch of geophysics. The contributions already made to the

knowledge of the earth have modified many formerly held theories and have furnished facts of vast economic importance beyond the realm of observational geology. Geologists should be grateful and should do their part in encouraging further geophysical investigations.

Let us recognize the broadening horizon of the field of geology. It has already become too broad for any one man to encompass the whole. Educators cannot hope to be able to train the students, in either the undergraduate or the graduate years, to make contributions in more than a limited few of the many inviting branches. Recognizing the situation, an attempt should be made to give the student sufficient insight into the existing problems, and sufficient training in the allied sciences, so that he can cooperate with the scientists of other fields in the study of the problems of the earth and can use the results they furnish. In addition, the geological student should be directed into the branches for which he is best fitted and in which he can undertake independent investigations.

Basic Science in Geological Curricula

By H. W. Straley, III,* Member A.I.M.E.

(New York Meeting, February 1941)

Some ten years ago the writer[1] made a survey of college catalogues to determine what sort of training geologists were receiving in basic sciences. In the light of this compilation and subsequent experience, he made the statement at the 1939 meeting of the Institute that apparently only in schools offering a curriculum in geological engineering or in the geological option of mining engineering curricula could geologists hope to receive the training advocated by Hubbert.[2]

In the former study, schools of engineering were excluded because the preparation was known beforehand. The present study aims to consider engineering schools in an effort to determine not only what basic studies are required but what use is made of them in geological courses of the third and fourth years.

The present study combined the method of consulting catalogues with a questionnaire. Letters were mailed to officials responsible for supervision of mineral industries curricula requesting information on: (1) the extent to which the engineering preparation of the first two years is actually used in the work of the last two; (2) the extent to which the engineering of the last two years is used in courses in geological engineering or geology; and (3) whether geologists or geological engineers teach descriptively or analytically.

Both methods of securing information are open to criticism; the former on the basis of the incomplete information supplied by university catalogues concerning prerequisites and curricula and the latter on the ground that the questions may be phrased poorly or given insufficient consideration by replying officials.

Fifty-six questionnaires were mailed and 39 (70 per cent) replies were received. Of the replies, 6 (11.3 per cent) were from colleges of liberal arts unconnected with engineering schools, 11 (20 per cent) were from schools having curricula in geological engineering and 22 (39 per cent) were from departments of mining engineering. The number of replies and their distribution were satisfactory in spite of the receipt of only six from liberal arts colleges. It should be understood that the universities of which the catalogues were examined were not necessarily the same in both compilations. No departments that are admittedly or known to be acting solely as service departments were recorded in the second study.

Table 1 shows that all professional schools require mathematics through calculus, whereas only 7 per cent of the liberal arts curricula expect the same level of preparation; only 73 per cent require trigonometry and 40 per cent college algebra. The proportion of geological engineering curricula requiring differential equations is higher than mining.

All of the engineering schools require general and analytical chemistry, whereas only 77 per cent of liberal arts curricula require general and 18 per cent analytical. Twenty-two per cent of the mining and 40 per cent of the geological engineering

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[1] References are at the end of the paper.

departments require additional chemistry, usually physical.

All of the engineering curricula require a year or more of college physics whereas only 48 per cent of the liberal arts list such a requirement.

All engineering curricula include drawing, descriptive geometry, and surveying (some of the mining engineers have two years of drafting), whereas only 22 per cent of the arts have drawing, 11 per cent descriptive geometry, and 15 per cent surveying. Mechanics (including hydraulics and strength of materials) is required in all mining curricula and in 90 per cent of the geological; electricity and heat in 83 per cent of the mining and 70 per cent of the geological. Forty-four per cent of the latter and 17 per cent of the former require additional courses in engineering other than mining or geological. None of the liberal arts colleges requires such courses.

Table 2 is a compilation of replies to the questionnaire sent to officials of mineral industry curricula. Although most of the answers were perfectly clear and could be interpreted with ease, a few had to be compared with catalogue material or an enclosed letter to be compiled properly.

With liberal arts preparation as indicated in Table 1, use cannot be made of basic science in teaching intermediate courses. It follows that a larger proportion of the replies should be in the "not at all" row of question 1 for that group. The same reasoning applies to question 2, for without preparation in elementary basic science a class would be completely baffled by the introduction of material from intermediate basic science courses. Without the preparation in basic sciences it would be difficult, if not impossible, to analyze quantitatively the facts of geology, so that question 3, as well, should show a larger proportion of replies in the descriptive row.

Departments of geological engineering

TABLE 1.—*Distribution of Requirements*

Subject	Arts				Mining		Geological	
	Number 1930	Per Cent	Number 1940	Per Cent	Number	Per Cent	Number[e]	Per Cent
Mathematics:								
Entrance	18	66.7	26	95	18	100	10	100
Algebra	6	22.3	11	40	18	100	10	100
Trigonometry	7	25.9	20	73	18	100	10	100
Analytics	5	18.5	1[b]	4	18	100	10	100
Calculus	2[a]	7.45	2[b]	7	18	100	10	100
Other					2	11.1	2	20
Chemistry:								
Entrance	2	7.45	2	7	2	11.1	4	40
General			21[c]	77	18	100	10	100
Analytical			5	18	18	100	10	100
Other					4	22.2	4	40
Physics:								
Entrance	1	3.7	2[d]	7	3	16.65	4	40
General	13	48.3	13	48	18	100	10	100
Engineering:								
Drawing	3	11.1	6	22	18	100	10	100
Descriptive geometry			3	11	18	100	10	100
Advanced drafting					6	33.35	2	20
Surveying	2	7.45	4	15	18	100	10	100
Mechanics	1[a]	3.7			18	100	9	90
Electricity and heat					15	83.3	7	70
Other					3	16.65	4	40
Schools	27		27		18		10	

[a] One requires mechanics and calculus for a major in physics and seismology (geology) but not for seismology and geology.
[b] One requires either mathematics through calculus or intermediate chemistry.
[c] General chemistry is required for mineralogy in only two schools.
[d] One specifies a course in either chemistry or physics as a prerequisite for elementary geology.
[e] This column includes two institutions in which geology is administered by the engineering school but in which the degree conferred is Bachelor of Science in Geology or Mining Geology instead of Bachelor of Science in Geological Engineering.

appear to make slightly more use of basic science and engineering than departments of geology in mining engineering schools. One may conclude that this arises from: (1) the presence of those with liberal arts preparation in the geological courses in the mining schools where departments of geology are not always controlled by the school of engineering, and their entire absence from departments of geological engineering; and (2) the fact that geological engineering is under fire at present from influential sources and the personnel has become quite conscious of the necessity for a quantitative, analytical approach.

In defense of liberal arts colleges, it must be admitted that frequently they advise more adequate training in basic sciences than requirements indicate. However, until such time as they explicitly state that they *require* this preparation, they cannot honestly use it in instruction.

Bucher,[3] Krumbein[4] and Slotnick[5] have suggested chemistry, mathematics through calculus, and a year of physics. The question arises as to where these subjects are most likely to be included in the training of geologists. This compilation indicates that the liberal arts colleges are not offering the training the new geology demands, and that schools offering a geology option in mining engineering or geological engineering are not only requiring such preparation but are using it.

The question will be raised as to why the liberal arts college cannot make the transition readily. The deans and heads of departments at engineering schools are accustomed to prerequisites. Contrariwise, the deans and heads of departments in liberal arts colleges are accustomed to permitting students to take courses with a minimum of prerequisites.

There seems, then, but one conclusion—that encouragement should be offered to the schools initiating geological engineering and extension of the geology option in mining engineering. This should not be taken to indicate that encouragement should not be offered to liberal arts institutions attempting to do the same thing, but one must realize that the liberal arts institution is dominated by tradition.

TABLE 2.—*Replies to Questionnaires*

Subject	Liberal Arts		Mining[a]		Geological[a]	
	Number	Per Cent	Number	Per Cent	Number	Per Cent
1. Extent to which pre-engineering of first 2 years is used in last 2:						
Not at all	3	50				
Qualitative	3	50	6	28	3	27
Quantitative			13	62	7	64
2. Extent to which engineering of last 2 years is used in geological teaching:						
Not at all	4	67	1	5		
Qualitative	2	40	7	33	3	27
Quantitative			11	52	7	64
3. Is the teaching of geological subjects descriptive or analytical?						
Descriptive	1	17	1	5		
Analytical	1	17	10	42	6	55
Do not know	4	80	9	41	4	36
Avoided answering			2	9	1	9
No geology option			1	5		
Number of schools	6		22		11	

[a] One school gives *mining geology* and another *geology* in the engineering school; both have been included under geological engineering.

REFERENCES

1. H. W. Straley, III: Deficiency in Mathematical Training Required of Geologists. *School Sci. and Math.* (Oct. 1932) 745–747.
2. M. K. Hubbert: Status of Geophysics in a Department of Geology. *Trans.* A.I.M.E. (1940) 138, 34–52.
3. W. H. Bucher: The Nature of Geological Inquiry and the Training Required for It. This volume, page 342.
4. W. C. Krumbein: Influence of Geophysics and Geochemistry on the Professional Training of Geologists. This volume, page 326.
5. M. M. Slotnick: The Education of an Exploration Geophysicist. This volume, page 337.

An Arts and Science Curriculum in Geophysics

By J. B. Macelwane,* Member A.I.M.E.

(New York Meeting, February 1941)

Geophysics differs from geology and physics in many respects. In the first place, geophysics is a complex science embracing the fields of seismology, geomagnetism, geoelectricity, geodesy, meteorology, volcanology, physical oceanography, physical hydrology, tectonophysics and exploration geophysics. Geology is also a complex science and so extensive in its various fields that no one can master them all, and no part of geology deals in any sense with several of these fields of geophysics. In the second place, geophysics makes use of methods and instruments that are derived primarily from the science of physics. Geology, on the other hand, has methods of its own and it draws its borrowed techniques and its instrumental equipment not only from physics but also and perhaps primarily from chemistry and biology. The difference, therefore, between the geophysicist and the geologist lies partly in the phenomena that are observed, partly in the methods and instruments with which each carries on his exploration; but partly also, and perhaps principally, in the habitual attitude of mind and in the background of specialized training with which each approaches the problems presented by this planet of ours. The geologist as such, therefore, is no geophysicist.

On the other hand, the physicist is not a geophysicist either. Isolation of each problem in a closed laboratory system under complete control is fundamental to the methods of the physicist. The geophysicist must apply physical instruments and physicomathematical reasoning to the study of physical quantities in their undisturbed natural environment.

What, then, is a geophysicist? In the sense that he is a trained expert in all of the geophysical sciences, I do not believe that such a person ever existed. It would be beyond the possibilities of a single lifetime. I think there is confusion in our ideas and in our use of terms. We are not all thinking of the same thing when we say *geophysics* or *geophysicist;* yet we seem to talk as though we were. It is as absurd to say that the whole of geophysics belongs to geology because the field of a particular type of geophysicist—the exploration geophysicist—calls for some knowledge of geology as it would be to say that the whole of biology belongs to geology because a particular type of biologist—the paleontologist—needs some knowledge of geology.

Development of a Geophysicist

Since it is impossible to become an expert in all the fields of geophysics, and since students entering college seldom know the field they will choose as a career, what would we suggest as the best general preparation for work in geophysics, whether as a meteorologist, an oceanographer, a seismologist, a geodesist, a geomagneticist, a volcanologist, a tectonophysicist, a hydrologist, or an exploration geophysicist? We may distinguish five phases in the development of a geophysicist: (1) his mathematical and scientific studies in high school; (2) the general mathematical and scientific

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courses at the lower division or junior college level; (3) the advanced, intensive courses at the upper division or senior college level; (4) the more advanced courses and the research of the graduate school, and (5) the apprenticeship in the candidate's chosen field.

The more mathematics and physics the student learns in the first two of these stages, the less time he will lose in the process of becoming a geophysicist. If he is looking forward to some of the branches of geophysics—for example, to exploration geophysics—he must also have chemistry and geology. At the third or upper division level our aspiring geophysicist will be in a position to begin the study of geophysics while continuing his mathematics and other college subjects. Geophysical theory is mostly physics, it is true; but it is a type of physics that is scarcely obtainable in a modern physics department, with its emphasis on nuclear physics. The type of advanced undergraduate course to which I refer is, for example, the plumb line and the figure of the earth, sea level, kinds of latitude and their variation, the earth's gravitational field, theory of attraction, Newtonian potential, tides, higher derivatives of potential and the theory of the torsion balance, absolute and relative measurements of gravity, gravity anomalies and their causes, free air and Bouguer corrections, theory of isostasy, magnetism, magnetic properties of metals, rocks and minerals, the earth's magnetic field and magnetic potential, magnetic measurements, geographic and temporal variations of the earth's magnetic field, magnetic anomalies, magnetic storms, theories of the origin of the earth's magnetic field, electric and electromagnetic theory applied to the earth and the atmosphere, self-potentials, vertical potential gradients, earth currents, ionized layers, atmospheric charges, elastic stress and strain, body waves of dilatation and curl, surface and bound waves, head waves, refraction and reflection of elastic waves, resonance, coupled systems, seismometers, equations of free, damped and forced motion of structures and pendulums, theory of transducers, amplifiers and filter systems, general galvanometer theory, thermodynamics and hydrodynamics of the atmosphere, of the oceans, of molten rock and the like. All this is fundamentally physics; yet what modern physics department would approve such an undergraduate concentration as meeting its requirements even if the courses were made available?

You say, postpone all this to the graduate level. I admit that you cannot make a competent geophysicist without graduate study and a postdoctorate apprenticeship. President Hotchkiss[1] quoted a friend of his as saying that "to be a real geophysicist a man should have a doctor's degree in mathematics, another one in physics, and another one in geology." I should like to add to the list another doctor's degree in *geophysics*. However, we must be realistic.

There will always be a place near the top of the ladder for the competent, fully trained geophysicist. Also, there are a large number of subordinate positions to be filled; and men with some geophysical training are needed to fill them.

Training of Subordinates

Let us restrict our discussion now to exploration geophysics. There is need for observers and computers in the field. Men with bachelor's degrees are being hired. Shall we not give these men the best training possible in four years? It must not be *ad hoc* training in techniques if it is to fulfill the desires of employers. Each company wishes to instruct its trainees in its own technique. The more solid scientific geophysical, physical, mathematical and geological background the graduate has acquired, the more readily he will see the reason for a particular technique and the more intelligent use he will make of it.

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[1] W. O. Hotchkiss: Discussion on Geomagnetic Exploration with the Hotchkiss Superdip. *Trans.* A.I.M.E. (1929) 81, 198. Geophysical Prospecting.

Complete Curriculum for the B.S. Degree,[a] *St. Louis University*

LOWER DIVISION COURSES

Freshman Year

ENGLISH	Freshman English (6)*
CHEMISTRY	General Inorganic Chemistry (8)
MATHEMATICS	College Algebra (3)*
	Trigonometry (3)*
	Plane Analytic Geometry (3)
GEOLOGY	Introductory Geology (4)
	Historical Geology (2)
RELIGION	Orientation Course in Religion (2) } for Catholics*
or	Catholic Life and Worship (2) } for Catholics*
PHILOSOPHY	Foundations of Morality (2) } for non-Catholics*
	Training of the Will (2) } for non-Catholics*
PHYSICAL EDUCATION	Freshman Course (cr)*

Sophomore Year

ENGLISH	Study of Literature (6)*
FOREIGN LANGUAGE	German (8)*
PHYSICS	General Physics (8)
GEOLOGY	Mineralogy (4)
RELIGION	Catholicism and the Modern Mind (2) } for Catholics*
	Revelation and the Modern Mind (2) } for Catholics*
HISTORY	Survey of European Civilization (6)*
PHILOSOPHY	Logic (3)*
SPEECH	Fundamentals of Speech (2)*

UPPER DIVISION COURSES

Junior Year

MATHEMATICS	Differential Calculus (3)
	Integral Calculus (3)
PHILOSOPHY	Philosophy of Being (3)*
	Philosophy of Man (3)*
GEOLOGY	Petrology (4)
	Tectonic and Structural Geology (3)
GEOPHYSICS	Introduction to the Geophysical Sciences (3)
	Geomagnetism and Magnetic Prospecting (3)
	Electromagnetic Theory and Electrical Prospecting (3)
FOREIGN LANGUAGE	German (8)*

Senior Year

PHILOSOPHY	Ethical Theory (3)*
	Social Ethics (3)*
	Survey of Systematic Philosophy (3)*
GEOLOGY	Economic Geology (3)
	Advanced Field Geology (2)
GEOPHYSICS	Earthquakes and Seismological Engineering (2)
	Elementary Seismometry (3)
	Practical Seismology (3)
	Seismic Prospecting (3)
	Gravity Prospecting (3)
PHYSICS	Radio (2)

[a] Starred courses are nonscientific degree requirementsi n the College of Arts and Sciences. The numbers in parentheses are credit hours required.

It would seem evident from what has been said that the undergraduate can get all the geology and mathematics he needs in existing departments but he cannot get all the physics he needs in the physics departments. A department of geophysics is needed not only to supply this want but to do it in the atmosphere of the other geophysical sciences and with the outlook and attitude of the scientific and professional geophysicist. Nowhere else than in a department devoted to geophysics can the student secure that fine balance of judgment between rigorous physicomathematical theory and the limitations of attainable laboratory and field results that is expected of the exploration geophysicist.

With these realistic and practical considerations in mind, the Department of Geophysics of Saint Louis University has worked out a curriculum in exploration geophysics, which meets the requirements for graduation of the College of Arts and Sciences, with lower division prerequisites and an upper division concentration consisting of a major in geophysics embodying nearly all the topics enumerated above as well as a minor in geology.

This curriculum has been tried out. The first graduates are all enthusiastic about their training. However, even the first of them have not been in the field long enough to test its ultimate effect on their careers as they grow older. One of the consequences to be expected is a realization of the inadequacy of their training and a desire to come back for graduate study.

A Geophysics Option in a Comprehensive Earth-science Curriculum

By H. Landsberg,* Member A.I.M.E.

(New York Meeting, February 1941)

The curriculum presented here is an outgrowth of discussions by the Committee on Geophysics Courses of the A.I.M.E. in previous years. It had to be a compromise between the desires voiced by employers of geophysicists, professional geophysicists and the possibilities at an average college. There one has to face the questions of the available teaching staff, the inertia of administrators and teachers set in their ways, and the red tape involved in modernizing antiquated curricula. It is, of course, not ideal to have colleges and universities lag 10 years behind the times. Rather, instead of being prodded by industry, they should be ahead of industrial needs. There should also be a certain amount of leeway for the student in any college curriculum.

All these points had to be considered in drawing up a curriculum, which, instead of being narrowly termed "geology" or "geophysics" was rather called "earth science." It gives the student a chance to specialize in one of the various branches represented by teachers on the faculty of The Pennsylvania State College, giving as options Geology (with subdivisions of Mineralogy and Paleontology), Geophysics, Geography, and Meteorology.

Table 1*A* represents the option of geophysics in the curriculum that envisages that a student may want to make his career in any of the fields encompassed by the American Geophysical Union or in geoexploration. This is, of course, only the start of an education that in most cases will have to be followed by graduate work for complete professional training.

The outlined curriculum is definitely of an engineering type and is identical for all of the four options mentioned for the first two years. Specialization will start in the junior year but even thereafter the branches are kept as closely allied as feasible in order to permit a student to change from one to the other (e.g., because of a different aspect in the employment situation) with a minimum of additional work.

Table 1*B* shows the geophysics option according to subject matter, indicating the considerable amount of work in the fundamentals of mathematics, physics and chemistry with a liberal number of geology courses, and some engineering. The courses in the field of geophysics are limited—just two lecture courses as a general introduction and one field course, to permit the student a visualization of the correlation between mathematically analyzed physical data and the geological realities. Thesis work is considered essential to teach the student, while he is still in college, some things S. F. Kelly has mentioned as desirable: (1) following of instructions for somewhat independent work; (2) organizing of material, and (3) producing a readable report. This, together with the personal contact with the advising faculty member, will help in forming a student's personality. The seminar course attempts to get the student into the habit of reading current literature, so that he can keep abreast of the times.

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Table 1.—*Curriculum in Earth Sciences,*[a] *The Pennsylvania State College*

A. Major in Geophysics

First Semester	Second Semester
Freshman Year	
Inorganic Chemistry (5)	Qualitative Analysis (5)
Engineering Drawing (2)	Geography of Mineral Resources (2)
English Composition (3)	English Exposition (3)
Physical Geology (3)	Historical Geology (3)
Trigonometry (4)	Analytical Geometry (4)
Mineral Industries (1)	
Physical Education (1)	Physical Education (1)
R. O. T. C. (1½)	R. O. T. C. (1½)
Sophomore Year	
Differential Calculus (3)	Integral Calculus (3)
Elementary Mineralogy (3)	Petrology (2)
General Physics (3)	General Physics (3)
Physical Measurements (2)	Physical Measurements (2)
Surveying (4)	Quantitative Analysis (5)
Physical Education (1)	Physical Education (1)
R. O. T. C. (1½)	R. O. T. C. (1½)
Approved Elective (3)	Approved Elective (1)
Junior Year	
Physiography of U. S. (3)	Economic Geology (3)
Differential Equations (2)	Curve Fitting (1)
Vector Analysis (3)	Sedimentation (3)
General Geophysics (3)	Applied Geophysics (3)
Precision of Measurements (1)	Report Writing (2)
Physical Mineralogy (3)	
Approved Elective (3)	Approved Electives (6)
Summer Practicum: 3 weeks Geologic Surveying; 3 weeks Geophysics Field Work.	
Senior Year	
Metallic Mineral Deposits (3)	Geology of Oil and Gas (3)
Structural Geology (3)	Petrography (3)
Analytical Mechanics (3)	Measurements with Oscill. and Tube Circuits (3)
Principles of Economics (3)	Seminar (1)
Thesis (3)	Approved Electives (7)
Approved Elective (3)	

B. Major in Geophysics Arranged According to Subject Matter

Mathematics (20)	Geology, Mineralogy, Geography (41)
Trigonometry (4)	Physical Geology (3)
Analytical Geometry (4)	Historical Geology (3)
Differential Calculus (3)	Economic Geology (3)
Integral Calculus (3)	Sedimentation (3)
Differential Equations (2)	Metallic Mineral Deposits (3)
Vector Analysis (3)	Geology of Oil and Gas (3)
Curve Fitting (1)	Structural Geology (3)
Chemistry (15)	Geological Camp (3)
Inorganic Chemistry (5)	Elementary Mineralogy (3)
Qualitative Analysis (5)	Petrology (2)
Quantitative Analys. (5)	Physical Mineralogy (3)

[a] Numbers in parentheses are credits. One credit corresponds to 1 semester hour of lecture, 3 semester hours of practicum or 1 week of camp.

TABLE 1.—(*Continued*)

Physics (17)
- General Physics (6)
- Physical Measurements (4)
- Precision of Measurements (1)
- Analytical Mechanics (3)
- Measurements with Oscill. and Tube Circuits (3)

Engineering (6)
- Engineering Drawing (2)
- Surveying (4)

Other Subjects (38)
- Economics (3)
- Physical Education (4)
- R. O. T. C. (6)
- Approved Electives (25)

- Petrography (3)
- Geography of Mineral Resources (2)
- Physiography of the U. S. (3)
- The Mineral Industries (1)

Geophysics (13)
- General Geophysics (3)
- Applied Geophysics (3)
- Geophysical Camp (3)
- Seminar (1)
- Thesis (3)

English (8)
- Composition (3)
- Exposition (3)
- Report Writing (2)

Among other subjects are listed approved electives, which are there to help a student. No university administrator or professor is in a position to exactly fit the needs of an individual student in advance. The student should have a chance to follow his own inclinations. Often a young person has ideas of his own, and these should not be stifled by curricular rigidity. It ought to be remembered that it is the responsibility of the student to find and hold a job, and often one who has followed his inclinations will be a better adjusted individual than one who has been directed too much. Usually, a student welcomes suggestions from faculty members for filling his electives. When he is fit for graduate work, the necessary foreign languages will find their place among the electives.

In Table 2 a comparative summary of various options is given. In considering the distribution of subjects it should be remembered that the curriculum developed from a straight geology curriculum hence the present geological option is the most rigid of all, because the whole is a compromise in which the original field has maintained most of its particular setup.

TABLE 2.—*Comparison between Options in Earth-science Curriculum*

CREDITS TAKEN IN VARIOUS SUBJECTS

Subject Matter	Geophysics	Geology	Meteorology	Geography
Mathematics	20	14	30	17
Chemistry	15	18	15	15
Physics	17	10	22	10
Engineering	6	6	4	2
Geology	24	39	6	12
Mineralogy	11	21	5	5
Geography	5	5	12	27
Geophysics	13	0	0	0
Meteorology	0	0	20	6
Mineral Industries	1	1	1	1
English	8	8	8	8
Economics	3	3	3	3
Nature Education	0	0	0	3
Physical Education	4	4	4	4
R. O. T. C.	6	6	6	6
Electives	28	18	29	[illegible]9

Discussion on

Influence of Geophysics upon Geology Curricula*

(New York Meeting, February 1941)

The papers discussed in the following pages were presented during two sessions of the Geophysics Education Committee of the Mineral Industry Education Division on Feb. 17 and 18, 1941. At the first meeting, to consider the "Influence of Geophysics upon Geology Curricula," this Committee was joined by the Geophysics and Mining Geology Committees of the A.I.M.E., the Society of Economic Geologists, representatives of the American Geophysical Union, and delegates from the Committees on College Curricula and on Applications of Geology of the American Association of Petroleum Geologists. Quentin D. Singewald and Sherwin F. Kelly presided. At the ensuing session, especially emphasizing the integration of geology, physics and chemistry for the solution of earth problems, the joint participants with the Geophysics Education Committee were the Geophysics Committee, and representatives of the American Geophysical Union and of the Committee on College Curricula of the American Association of Petroleum Geologists. Richard M. Field and W. R. Chedsey presided. In the following summary of the discussion at the two meetings, written discussion submitted subsequently is not differentiated from that offered orally at the session.

A provisional report of the Geophysics Education Committee was presented at the second session, and some of the following discussion refers to it. This report has not been printed (it is anticipated that a more comprehensive, final one will be rendered at the 1942 annual meeting). A few mimeographed copies of this provisional report were made.

Dr. W. P. Haynes presented some notes prepared by Dr. F. H. Lahee, Chairman of the American Association of Petroleum Geologists' Committee on College Curricula. This Committee's inquiries reveal the general opinion that a four-year academic preparation is inadequate, five or six being advisable. The fundamentals, mathematics, physics, chemistry, and English composition, should be stressed in the first three years, with specialization in the last two or three years. Some companies provide an apprenticeship period, and themselves give additional training. During academic years more attention needs to be given to engineering training, to field mapping, and in geology to stratigraphy and sedimentation. The amount of mere memory work should be cut, and men trained to observe and reason. Dr. Lahee emphasized the need of more adequate preparation in English composition, because of the inability of many graduates to compose acceptable reports.

Sherwin F. Kelly pointed out that much time in university training, which ought to be devoted to technical subjects, was taken up with English courses. He emphasized that it is the part of the universities to demand of the high schools that the students they send to the university be properly trained to speak and write English. Prof. W. T. Thom protested against the crowding of high-school material into already overcrowded college curricula.

C. E. Dobbin, chairman of the Committee on Applications of Geology of the American Association of Petroleum Geologists, described briefly the work of his committee in publicizing geology, and said that it found a widespread popular interest in the subject but a lack of appreciation of its importance. He recommended that attempts to coordinate the works of geologists and geophysicists be expanded somewhat toward the further developing and encouraging of a "species of geopolitician" capable of assisting the progress of geology and geophysics by more vigorous advertising of

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their worth and works to appreciative and influential laymen.

Two students, WILLIAM THURSTON and RICHARD MAHARD, voiced protests against the long academic preparation being envisaged for geologists. Apropos of the publicizing of geology, one of them commented that he had not heard of that science until he got to college. Prof. W. T. THOM called attention to the educational movies now available, some of them showing geological processes, and suggested that they be more widely utilized, especially in grammar schools.

PAUL WEAVER brought out the importance of the geologists' role as arbiter between the various alternative solutions that may be offered as the result of geophysical analyses. Observed geophysical data will not give a unique solution in tectonic terms, and the geologist must apply his observational ability and knowledge of the time element in choosing the most probable geological answer.

DAVID B. REGER suggested that, as geology is the science of the earth, it is the geologist's duty and prerogative, with all due respect to the tools he must use, to "run the show himself." Prof. HELMUT LANDSBERG replied that the geologist should have at least enough knowledge of exact physical and mathematical sciences to know what his colleagues and subordinates are doing.

M. K. HUBBERT drew from his own teaching experience to point out that he had found it possible to give more advanced work to engineering students in courses in introductory general geology than to the average graduate student in geology, owing to the pre-engineering training given in physics and mathematics. That the high schools are failing miserably to give their students adequate preparation for university work, he felt was an inescapable fact. Nevertheless, the universities could take the material sent them and with proper instruction turn out first-class technical men. That is just what the engineering schools are doing. It would not require eight years of college work, and could be given in less time than the standard training now provided for geologists. He emphasized the inadequacy of conventional geology, and the inadequate preparation given students desiring to study geology. One of the main difficulties in revising present-day curricula to meet desirable standards is that most of the geology professors are not themselves prepared to handle the subject on the proposed level. This will require the gradual replacing of the older-school geologists, as retirements make vacancies, with men trained thoroughly in the basic sciences, especially physics, mathematics and chemistry. Geology curricula today are packed with "busy-work" courses, he pointed out, and so-called "advanced work" is largely repetitive, expanded elementary work that wastes the students' time. What we need is scientific training for students who are to become earth scientists; universities at the present time are not fulfilling that need, but it is quite possible for them to do so.

The advantages to a geologist of knowing something of engineering were also stressed by RICHARD W. SMITH. He conceded that a five-year curriculum, as proposed by W. C. KRUMBEIN (T.P. 1327) was a decided improvement over the curricula in most colleges, but found it weak in not including any mining engineering, ore dressing, and metallurgy. Nearly every physical geologist, at some stage of his career, must delve into economic geology, and a knowledge of mining engineering and related subjects will enable him better to evaluate the importance of a mineral deposit, and the amount of detailed geologic study that it warrants. Personally, he has used these subjects more than higher mathematics.

General agreement with Krumbein's "blueprint" for the qualifications of a properly trained geologist was expressed by JOHN B. LUCKE. He also felt that, in many geology departments, the basic sciences have not received the attention due them. The change to a five-year curriculum may be entirely admirable, but only for the existing geology departments that have professional fitness as their *sole* objective. The dangers of early overspecialization need not be emphasized again, and it is worth noting that most medical schools, and a few engineering ones, prefer to give their students fully professional work only after they have completed a four-year liberal education. He suggested an alternative solution, the establishment of two undergraduate curricula in geology; one would be openly nonprofessional, a purely cultural course; the second would be a "preprofessional" curriculum, embodying many basic sciences, but stopping short of professional competence. The

latter course would automatically lead to full professional training in graduate or professional schools equipped to provide it.

A student, JOHN ROBINSON, voiced the complaint that important courses he knows he should have he cannot take, although they are listed in the catalogue of the university he attends, because to do so would deprive him of the proper credits required to obtain his diploma! This situation was further commented upon by TAISIA STADNICHENKO, who told of the opposition to certain proposed science courses, expressed by the Classics Department in an eastern college. SHERWIN F. KELLY spoke of hearing recently that a geophysics curriculum had finally been established in a large university, but only over the opposition of the professors of the classics, who saw themselves being shoved out of the picture.

Apropos of the St. Louis University curriculum, J. J. LYNCH, S.J., inquired of J. B. MACELWANE, S.J., why he put physics in the sophomore year instead of in the freshman year, and why he separated the mathematics of the freshman and junior years. He also suggested interchanging the chemistry and physics. J. B. MACELWANE replied that his curriculum (T.P. 1380), like all curricula, was a compromise with the college requirement for graduation. Chemistry was put in the first year together with geology because geology needs the chemistry, but the program was too heavy to admit physics as well. The mathematics had to be separated because of the heavy college requirements in the second year. The difficulty of interchanging physics and chemistry is one of sequence. Chemistry is useful for geology and mineralogy, and the latter is a prerequisite for petrology. To take general and historical geology with mineralogy and chemistry in the sophomore year would crowd the program. Therefore introductory geology, historical geology and chemistry are put in one year, mineralogy and physics in the next, and petrology in the third.

Dr. W. R. CHEDSEY pointed out that he knew something of the situation at both Professor Landsberg's and Father Macelwane's institutions, and he thought he could explain certain differences, which would help to clarify part of Father Lynch's questions. At Pennsylvania State College the geophysics is taught with an engineering background, and therefore has to fit in, from the administration viewpoint, to the conditions of mathematics, physics and chemistry that naturally result from such a program. At St. Louis University, on the other hand, and probably at Fordham University, the conditions are different. There is not the same limitation on the credit courses in mathematics in the freshman year that there is in an engineering school. In the latter, mathematics is a prerequisite for physics, as it plays the part of a tool in the engineer's conception of his physics course.

The training of a geophysicist should be fundamental, J. B. MACELWANE continued, and not a drilling in techniques and rules of thumb. For this reason, the courses designated as prospecting are actually courses in fundamental physics, but of a type not available in the physics department. Most physics departments are interested in nuclear physics, and not at all in those phases of physics headed directly for the study of the earth. Therefore, of the geophysics courses in the curriculum, 90 per cent is physics, 5 per cent is technique, and 5 per cent is geology.

Agreement with the viewpoints set forth at the second meeting was expressed by E. A. ECKHARDT. He said he was pleased with the papers presented, especially as he felt they were leading to a satisfactory composite view. The difficulty of forecasting what fields of professional activity will be available when a man graduates, as well as what his inclinations and objectives will be, demand that the training be as fundamental as possible. Specialized subjects, such as prospecting, should be given only to provide the student with a general idea of the fields of application. Fundamental training in earth sciences, in mathematics, in chemistry, are the important things. But a good course does not consist of a mere aggregation of existing courses in those subjects. The courses in geology, mathematics, and physics should be reviewed with the idea of coordinating them—physics with geology, for example. Physics teachers might well look over their curricula to see whether the emphasis might not be shifted a little when they have students looking forward to a career in geology or geophysics. Courses to be given people studying the earth sciences need to have their components modified, so as to fit together as a homogeneous whole. As to the qualifications of a modern

geologist, he said that if the abilities of a man considered in geological circles to be a good geologist, and of one considered in geophysical circles as a good geophysicist, could be combined in a single person, he would be a good modern geologist.

Agreement with the points brought out was also expressed by W. P. HAYNES. He said that ordinary college training does not give students just the right background needed for practical application, so either they must be specially trained afterward for six months or a year by the employing company, working on special types of exploration geophysics problems, or the teaching must be reorganized so as to cover many more of these points than it does now. With geochemistry getting to a stage where definite problems are coming up, some of the chemical courses might be adapted so as to be of more help. Certain phases of mathematics might advantageously be emphasized, as a result of a reexamination of such courses. Through reorganizations in physics, chemistry and mathematics, better training could be given without taking so much time. In this way the course might be kept down to a four-year program, and any subsequent company training be reduced to a minimum.

L. W. BLAU agreed that our schools should put less emphasis on immediate applications. At the first session, every speaker thought that physics, mathematics, chemistry and geology should be studied by a geologist. Yet in spite of this unanimity of opinion, virtually nothing is being done about it. Sooner or later, as it becomes evident that students with the training in fundamentals are getting the jobs, the universities will be obliged to change their geology curricula accordingly. If they do not, they will find new departments taking over earth-science subjects, and the geology department relegated to the attic.

Commenting on the courses described by J. B. MACELWANE and H. LANDSBERG, he expressed the opinion that the physics, chemistry and mathematics offered were the minimum a geologist should have, but would be inadequate for a geophysicist. With only this training in the fundamentals, a man might be able to take geophysical data obtained by others and make maps, but would be incapable of doing any original work in geophysics. The remedy, he believed, would be to cut down the hours devoted to geology without cutting out any of the geology. In his opinion this is entirely possible because the present geology courses are overloaded with detail, and there is general lack of organization in the science. The time thus saved should be devoted to more work in physics, chemistry and mathematics.

L. D. LEET inquired whether L. W. BLAU's conception of the geophysicist to be trained would be as a physicist operating instruments or as a geologist interpreting geology. In his reply, L. W. BLAU said he saw no reason why a geologist or a geophysicist should hire an electrical engineer to collect the data; he should know something about it himself. The geophysicist should have devoted more time in college to physics, chemistry, mathematics, and economics. He should know enough geology to get along, and should read widely in it. H. LANDSBERG asked what sort of teachers should be on the faculty, to which L. W. BLAU replied that he believed in giving all students physics, mathematics, chemistry, biology, and geology to start with, letting them branch out later. With physicists and geologists on the college program, there would be no need for geophysicists on the faculty. L. D. LEET expressed his fundamental agreement with L. W. BLAU's contentions, and with his suggested courses of study. However, he felt that what is needed in these discussions is first a definition of aims, not of methods.

In its provisional report, the Geophysics Education Committee recommended that the training of geophysicists be confided to the department of geology. To this PROF. W. T. THOM took exception, relating that his study of the matter, including the examination of some 50 college catalogues, convinced him that some other arrangement will have to be the answer.

Dr. W. R. CHEDSEY explained his interest in these meetings as neither that of the geologist nor of the geophysicist, but rather from the multiple viewpoint of a mining engineer, an educator, and a college administrator. With geophysics emerging as one of the newest branches of thought, at least in the college field, a fine opportunity was presented to help it grow up logically instead of drifting unguided. A further important aspect was its relation to geology, and the improvement in the latter science that might result from the influ-

ence of geophysics upon it. Nevertheless, he felt strongly that the emergence of geophysics did not reduce the necessity for keen observational geology. However, geologists should not be afraid of mathematical formulas, nor should geophysicists be too dependent on their instrumental data.

The speaker pointed out that one of the big problems of the Education Division has to do with helping the college graduate to become oriented into industry. For this it is necessary to get employers to cooperate with the educators, a program that fits into what has been said about post-graduate training by some companies of young geophysicists and geologists entering their employ. He agreed that the college should concentrate on *fundamentals* and not try to teach details of current practice. Current details should enter only into a course designed to show how the fundamental subjects are brought together and put into application. Therefore a college can turn out only a semi-finished product, even with seven or eight years of training. Industry must then take these men and give them specialized, professional training. He made a plea that those interested in geology and geophysics cooperate with the Division in the general problem of the post-collegiate education of such college men.

While the widest possible variation of opinion is desirable at this stage of these discussions, it is now time to begin to eliminate the least important factors in the problem. We should draw into the picture the most important parts that can be handled by the colleges, and crystallize the parts that should be the function of the post-college phase of training. In this latter, industry and the college could work together to train these young men further in their own industry.

Dr. Chedsey then expressed the hope that there would be full cooperation with the Committee in preparing the next year's report, so that it would be in practically final shape. Those in college administration work need it, he said. There was no question that the discussions that have gone before have been of great benefit, as shown by the fact that there have been attempts to follow the early, tentative recommendations of the Committee. It is now necessary to crystallize more thoroughly all phases of thought on the subject.

Integration of Geology, Physics and Chemistry for the Solution of Earth Problems

REPORT OF GEOPHYSICS EDUCATION COMMITTEE OF MINERAL INDUSTRY EDUCATION DIVISION, A.I.M.E.*

(New York Meeting, February 1942)

For four years your Committee has been engaged in the study of problems connected with the educational preparation of professional geophysicists. The present report represents the conclusions drawn from the investigations and deliberations undertaken since it was first organized. These studies have shown that the evolution of geophysics has proceeded along lines that differed from those marking the advance of classical geology. The latter science developed as a descriptive one, dealing with directly observable terrestrial phenomena, and the elementary, rational explanations that could be offered therefor. The fact that these phenomena were also chemical and physical in nature was seldom given more than passing acknowledgment. During the last half century, however, a new approach to problems of terrestrial phenomena has become of greater significance. This new attack has come through the sciences of physics and chemistry, as the people trained therein have investigated the facts of the earth as problems in their respective sciences. This development has been chiefly at the hands of European investigators, and European universities have long recognized it by establishing departments or institutions of geophysics.

In the universities of North America, their arbitrary departmentalization into fields of physics, chemistry, astronomy, geology, etc., has prevented the academic recognition of such domains of science as geophysics and geochemistry. In consequence, the development of these subjects in the United States has been largely at the hands of nonacademic institutions, while the universities themselves are evidently in a state of confusion as to how the subject should be handled. In some places an attempt to teach geophysics is made in the physics department, in others in the geology department, in some in the engineering school, and occasionally as a cooperative effort; a Department of Geophysics is seldom found in North America. In some instances, proper academic planning has been precluded by interdepartmental jealousies, or by lack of appreciation of the significance of the subject.

For the background upon which these conclusions are based, the reader is referred to reports previously issued or sponsored by your Committee. The "First Report of the A.I.M.E. Mineral Industry Education Division's Committee of Geophysics Education, 1939," summarizes the replies received to question-

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The Committee

SHERWIN F. KELLY, *Chairman* M. KING HUBBERT, *Vice-chairman*

H. W. STRALEY, III, *Secretary*

C. H. BEHRE, JR.	W. B. HEROY	J. W. PEOPLES
L. W. BLAU	J. J. JAKOSKY	W. T. THOM, JR.
HENRI G. DOLL	W. C. KRUMBEIN	CLYDE WILSON
C. A. HEILAND	H. E. LANDSBERG	R. D. WYCKOFF
	J. B. MACELWANE	

naires sent to a large list of universities in the United States and abroad. These questionnaires were designed to reveal the manner in which the subject of geophysics was handled, and how the universities were equipped to teach it. The second report was entitled "Appendix to Report of Mineral Industry Education Division, A.I.M.E. Committee on Geophysics Education, 1940." This summarized the replies to another set of questionnaires, circulated to graduate professional geophysicists, and to employers of geophysicists. The purpose of this set was to discover how geophysicists and their employers evaluate present academic training in geophysics. Summaries of these two reports and the attendant discussions appear in the TRANSACTIONS of the A.I.M.E., volume 138, Geophysics, 1940.

The third, "Report of the Geophysics Courses Committee of the Mineral Industry Education Division, on the Integration of Geology, Physics and Chemistry for the Solution of Earth Problems," was a provisional one, in 1941. The present report completes it. In 1941, The Geophysics Courses Committee sponsored a symposium, "Influence of Geophysics upon Geology Curricula," in which several of the papers have a direct bearing on the question of geophysical education. Reference should also be made to papers by M. King Hubbert, C. A. Heiland and Dort Wantland, David A. Keys, and Danald C. Barton, and accompanying discussion (all in TRANSACTIONS A.I.M.E., volume 138, published in 1940.)

During its investigations, your Committee has not confined itself to considerations of the training required for an exploration geophysicist, but has envisaged the field in a broader sense.[1] The recommendations herewith set forth will doubtless require modification as experience grows and curricular shortcomings become evident; the present report therefore is not offered as the final word on problems of geophysical education.

Scope of Geophysics

At this point it is well to repeat the definition of geophysics adopted by this Committee since the inception of its work in 1938. The science of geophysics was defined, for the purpose of this investigation, as the *integrated application of the disciplines of physics, chemistry and geology, to the solution of problems involving the materials of our earth, their nature, movements and changes in energy states, and their transformations.* This definition embraces also the geophysical sciences that furnish data whose utilization for the purpose of discovering mineral bodies of economic value constitutes the art of geophysical prospecting. The definition is thus broad enough to include various branches of the physics of the earth, as well as prospecting activities, and the making of related instruments. It embraces the configuration of the solid, liquid, and gaseous portions of the earth, and their processes of change, which are problems in the mechanics of solids and fluids, in gravitational theory, thermodynamics, electricity and magnetism. In short, it must embrace all the branches of classical physics and physical chemistry, as well as radioactivity and other phases of nuclear physics.

There have already developed, as separate divisions of geophysics, the fields of Meteorology, Hydrology, Oceanography, Geodesy, Seismology, Vulcanology, Terrestrial Magnetism and Electricity, Tectonophysics, and various branches of applied geophysics in prospecting and engineering work. The science of geophysics, then, is the study of the earth regarded as a complex of physical and chemical phenomena.

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[1] Reference may be made to "Everyday Importance of Geophysics Symposium," 1940, sponsored by the Committee on Geophysical Methods of Exploration, for discussions of geophysical endeavor in other than the exploration field.

Inasmuch as geology is the science of the earth,[2] unavoidably its study involves physical and chemical phenomena as well as conventional field relations. Therefore, any curriculum in geophysics necessarily constitutes an important part of a curriculum in geology, and should ideally be directed by the latter department. Actually, however, circumstances may prevent the immediate realization of this ideal, as many geology departments are not prepared to handle the subject on the level prescribed, owing possibly to a limited viewpoint on earth science. It is not the function of your Committee to make recommendations at the present time relative to geological curricula, however, except in so far as they may be required for the purpose of the present report. Existing departments of physics could conceivably give geophysical instruction, but a difficulty arises here from the fact that most of them are primarily concerned with research in nuclear physics. Geophysics, on the other hand, is mainly applied physics and involves principally the relationships of classical physics. It is thus closely related to engineering, which is also applied physics; consequently, in many cases the engineering school can effectively handle the teaching of geophysics. Another possible solution would be a thorough and close cooperation between the departments of geology and physics.

In many universities the above-mentioned departments and schools between them offer most of the material required for a geophysical education, at least on an elementary level. Because of the departmental organization, however, the student is forced to affiliate himself with a single department, whereupon his choice of courses is directed by the wishes of its administrators. If he then tries to secure adequate preparation for geophysics, he may be compelled to sacrifice his degree. Furthermore, the subjects offered furnish but the uncorrelated, raw materials of a geophysical education, and need to be integrated and applied to specific observational problems and phenomena of the earth. In view of these circumstances, the optimum place for geophysics in a university at the present time may well be as a separate institute or department. It could thus have its own staff and research facilities, with complete control over its curriculum, while maintaining close liaison with those other departments to which its students go for much of their foundation training. There should be nothing to prevent the eventual amalgamation of the departments of geology and geophysics.

Irrespective of the administrative setup that may be adopted in particular cases, this Committee thinks its report can be of maximum assistance to university administration if it presents definite curriculum requirements for the undergraduate training of geophysicists (Table 1).

Geophysical Curricula

Since there are several types of undergraduate schools whose students enter the profession of geophysics, such as schools of mines, engineering, technology, and colleges of arts and sciences, the same curriculum for undergraduate training of professional geophysicists will not satisfy the present needs of all types of institutions. The prime consideration in establishing any course of study, however, should be to fulfill the requirements for the students' envisaged careers, rather than to adapt it to the straightjacket of any preconceived academic formula. Your Committee has tried, nevertheless, to find certain common principles on which all can be expected to agree. The first of these is the necessity for maintaining a sound, cultural base in the training of any student. The second is the need of solid training in the sciences

[2] The principal divisions of the earth are the atmosphere, the hydrosphere, the lithosphere and the biosphere; the latter enters the field of geology mainly, but not exclusively, through its fossil manifestations.

of geology, physics, mathematics, chemistry and biology. The third is the necessity for theoretical training in geophysics, considered as earth physics and earth chemistry, as brought out by replies to the Committee's questionnaire in 1939.

Although the question of the organization and administration of the curricular embodiment of these three requirements must be left to each school for suitable solution, the Committee feels that no solution will be adequate unless two results are secured. First, the undergraduate course of study must be sufficiently broad and theoretical to permit a student to enter one of the several specialized fields in his graduate years; secondly, it must furnish the undergraduate with sufficient knowledge of geophysical science to enable him to assimilate rapidly and intelligently the various special techniques of the art of geophysical prospecting should he choose, as so many will, to accept immediate employment in the industry.

TABLE 1

The College[a]

1. *Cultural Background*

A survey of the humanities
History and geography

2. *Fundamental Science*

Mathematics through calculus
General physics
General chemistry
General geology
General biology
Astronomy

3. *Tool Subjects*

English composition and rhetoric; German
Drafting and descriptive geometry
Surveying, including plane table
Shopwork

The Division[a]

1. *Fundamental Science*[b]

Quantitative and physical chemistry
Heat, electricity and magnetism (including electronics and radio), and mechanics (including fluid mechanics and strength of materials)
Geology, including a thorough study of minerals and rocks, and a summer field course.
A broad, fundamental, theoretical course in earth physics and earth chemistry.

2. *Tool Subjects*

Engineering law, and a survey of other social studies
German

[a] By the term "College" is meant the first two years of University training. By the term "Division" is meant the third and fourth years of University training.

[b] It is recognized that in individual instances certain substitutions may be necessary on the divisional level. For example, meteorologists evidently do not need as much geology as is presented in this table.

The educational preparation of the geophysicist has only begun, however, when he receives his bachelor's degree. At that point in his education he will know only enough to learn how to do routine work in the field or office, and he will not be a research man capable of advancing his chosen science. The academic preparation necessary to give a man satisfactory training to start a career as a geophysicist comprises at least 6 years after high school. Preferably, he should carry out the advanced research work necessary for a doctorate. Your Committee has not proceeded, however, to the investigation of post-graduate academic training, or post-university study. These are subjects that had best be dealt with in separate reports in the future, after careful consideration and trial of the proposals submitted herein.

In all types of schools or colleges the courses of the first two years—variously styled Lower Division, Lower College, Junior College, College, and Freshman-Sophomore courses—must be broad and fundamental. These courses, however, may be classified, on the basis of objectives, into cultural and tool subjects and the indispensable sciences. It seems hardly necessary, in view of what has been written in recent years, to justify the inclusion of a cultural background. By "a survey of the humanities" (Table 1), is meant a broad survey course covering introductory psychology, philosophy, comparative literature, comparative religion, anthropology, ethics, education, and civilization. In brief, such a survey would attempt to give the student some idea of the cultural,

ethical, psychological and religious environment of the human race for the past 10,000 years.

The term "tool subjects" has been used to designate the studies that are neither entirely cultural nor basic science, but which are essential to the understanding and utilization of the fundamentals acquired in the basic science courses. Literature and creative writing are recognized as cultural subjects; but the correct, fluent and effective use of the English language is an indispensable tool of the geophysicist, so that composition and rhetoric are also tool subjects. The same may be said of foreign languages. A large amount of scientific literature is written in languages other than English, and any man hoping to do more than routine work must be able to ferret it out. German is the choice of this Committee because more literature on geophysics has appeared in it than in any other foreign language. A second choice would be Russian, because the geophysicists of that country have recently been very productive.

In practically all types of field work it is necessary to prepare and use maps, for which an elementary knowledge of surveying is essential. Descriptive geometry is so necessary in problems connected with three dimensions that its omission would be a severe handicap. A course in shop work is deemed advisable, with the thought that manual dexterity is essential for a man who must work with instruments, and that he should know something of how such instruments are constructed.

For the student who intends to enter the field of geophysics, the basic sciences are both cultural and tool subjects, therefore the courses in them must be more theoretical, more extensive and more thorough. This is especially true of chemistry, geology, mathematics and physics. These fundamental science requirements need no justification, but some elaboration may be useful, in giving greater precision to the contemplated content of these courses. In mathematics, lack of time probably will necessitate the postponement of differential equations to the graduate years, although its proper place is immediately following calculus. In physics, the inclusion of a large number of problems, both in laboratory and classroom, is highly desirable. Although the inclusion of a large number of experiments in which the students set up their own apparatus might result in an increase in the number of laboratory hours devoted to physics, this program is deemed necessary.

The general chemistry should include the elements of qualitative analysis, so that the student is prepared to proceed with quantitative analysis in his junior year.

General geology, falling in the sophomore year, should make use of the previously assimilated chemistry, and of the concurrent physics. It should include minerals and their alteration products, geological processes, historical geology, economic and engineering geology.

The biology on the college level should include elementary botany, zoology, physiology, and preventive medicine. The student should also qualify for the First Aid Certificate of the Bureau of Mines and/or the local Red Cross.

The courses of the third and fourth years—called Upper Division, Upper College, Senior College, Junior-Senior, the Division, etc.—are more advanced and more specialized. Quantitative and physical chemistry have been included in the Divisional level, and although the Committee recognizes the advisability of including organic chemistry, lack of time necessitates its postponement to the graduate years. The physics mentioned is self-explanatory, and requires no elaboration. The geology should include a thorough study of minerals and rocks, economic, petroleum and structural geology, stratigraphy, and a summer field course.

The broad course in earth physics and earth chemistry should deal with the static configuration of the earth's fields in addition to energy transformations in the earth and its components. These energy transformations involve gravitational, thermal, seismic, electrical, and magnetic phenomena, and chemical changes. The subject matter covered should include a survey of the divisions of geophysics mentioned earlier in this report, as well as a perspective of the techniques of geophysical prospecting.

Under the heading of the tool subjects, foreign languages have been discussed. As to social studies, the geophysicist must live in society and should know something of the social structure in which his life is to be spent and in which his work must be done. He should know the fundamentals of economics and the impact of science, particularly his own field of endeavor, upon the economic and social structure about him. As long as man is a social creature he will be governed by some sort of law. Your Committee looks upon an elementary knowledge of the rules of the game as essential to any person that calls himself educated.

At this point it is well to emphasize again that a student who has satisfactorily completed the studies outlined has not, however, completed his educational preparation for a career in geophysics or geology. He should plan to continue his training during several years of graduate work, and if possible qualify for a doctorate. If he is to pursue a career in geophysics on a research or investigatory level, he *must* have the requisite training. He should be familiar with physical chemistry, and with the theory of practically the whole range of classical physics, as well as with electron physics and radioactivity. The methods of measurement and experimental techniques in these fields should be known to him. Such a geophysicist obviously requires a knowledge of mathematics sufficient to fulfill the foregoing requirements—differential and integral calculus, differential equations, theory of complex variables including the theory of alternating current and mechanical oscillators, and the mathematical theory of such physical fields as fields of force, fluid, stress, thermal fields. Vector and tensor analysis would be included. A *thorough* knowledge of geology is also requisite. Evidently, the curriculum presented here represents only the minimum requirements of the undergraduate preparation for such advanced work.

The Committee recognizes the fact that the curriculum proposed is a difficult one, and that it may severely tax the resources of many educational institutions. Establishing a sound course in geophysics, be it emphasized, is not a minor undertaking, to be achieved by merely providing a survey of the subject. The magnitude and scope of geophysics require that administrative machinery be set up to handle a major undertaking, if it is to be well done. Unless an institution is prepared to set up courses essentially equivalent to the requirements outlined, the Committee recommends that it do not attempt the training of professional geophysicists.

Your Committee, realizing that the suggested curriculum is heavily crowded, thinks such a situation could be remedied, and room made for more advanced, sorely needed courses. This end could be achieved if the university authorities were to insist that students desiring to enroll in such a program of study be adequately trained by the high schools (Table 2). The secondary schools are now shirking the education of their students in many subjects that are essentially of high school or preparatory school level, thereby forcing the universities to take over this task, to the detriment of advanced education.

Table 2 presents an eight-year curriculum, comprising four years of high school and four years of college. If the high school is properly administered, any of its students

with normal intelligence should be able to read, write and speak the English language correctly. There would then be no reason to repeat the work, and take from 6 to 10 hr. at the college level. There was a time when college algebra and trigonometry appeared on many high school programs, and in view of the simplicity of these subjects, there is no necessity to postpone them to the college years. A knowledge of German grammar and simple reading should be gained in two years of high school study, so that one year in college should be sufficient to give the student working facility with the language. A second language, in the Romance group, preferably Spanish, could advantageously be taken as one of the electives. High school physics should give an introduction to general physics, and teach facility in solving problems. General chemistry, if properly taught in high school, can be made to cover one semester of college work.

Table 2.—*A Proposed Eight-year Curriculum*

High School or Preparatory School

English composition, rhetoric and literature
Mathematics through college algebra and trigonometry
Geography
History
Elementary and intermediate German
Biology, chemistry and physics
Mechanical drawing and drafting
Manual training and shopwork
Electives—especially to provide for the necessary classical and philosophical phases of a sound education

The College

A survey of the humanities
Analytical geometry and calculus
Differential equations
General physics
Analytical mechanics
General and analytical chemistry
Astronomy
General geology
Scientific German
Descriptive geometry
Surveying, including plane table

The Division

Physical chemistry
Organic chemistry
Heat and thermodynamics
Electricity and magnetism
Strength of materials and hydraulics
Geology
Geophysics
Engineering law
A survey of the social studies
Electives

A drafting course in high school would require the student to spend 360 hr. in the drafting room; in college, a four semester-hour course would require 144 hr., and a six semester-hour course would require 216 hr. at the drafting table. The Committee sees no reason why such a subject as drafting should not cover as much in one year on the high-school level as on the college level. The same amount of time would be devoted to manual training and shopwork; the year of high school manual training and shopwork could be even more complete than a college course utilizing a maximum of 72 hours.

Only two courses not in Table 1 have been introduced on the college level in Table 2—differential equations and analytical mechanics. Other requirements, however, have been made more inclusive. A student that has completed the first year of mathematics and physics is ready to take analytical mechanics, which provides an opportunity for a considerable broadening of the divisional curriculum. The physics could include more problems and laboratory exercises in which the student assembles his own equipment, because of his background of high-school training in physics. The calculus and analytical geometry are given in the freshman year, which should permit the course to be better organized than is usually possible. The sophomore chemistry should be taught from a physical viewpoint, made possible by the general high school chemistry and the two years of physics the student will have had. The opportunity to express chemistry in physical terms will permit a broader significance. Many students report that chemistry was nothing more than a rule-of-thumb procedure until they had

studied physical chemistry. The geology of the college level should include additional field and laboratory work. With the background indicated in Table 2, it should be possible for the students at the division level to attack their work with greater ease, and for the course of study to be broadened and deepened.

Wider Applications

Although, in preparing Table 2, your Committee had geophysics in mind, the high school and college portions of this curriculum could also be adopted as a standard for engineering. It is more complete in mathematics, science, drafting, and shop than is customarily demanded by engineering schools, and inculcates a more thorough knowledge of English and the ability to use it. Admittedly the high-school requirements are more rigorous than are now common in our secondary schools, but a student incapable of mastering the proposed subjects at that stage in his education will undoubtedly lack the mental capacity to profit from an academic preparation for a professional career.

For those not going to college, however, it should be pointed out that biology, chemistry, physics, and at least elementary mathematics, are fundamental subjects in our type of civilization, and should be taught, at least in their elementary aspects, to all high-school students. This is not to minimize the value of the classical and philosophical aspects of education, but to point out a student who studies only subjects in these latter classifications is not adequately prepared to adapt himself to the environment of today. He cannot be considered to have even the elements of an adequate schooling unless those scientific subjects be included therein. Therefore, since only a small proportion of students goes on to the university, the movement should not be toward lessening of the standards of high school education, but toward improving them by including elementary instruction in mathematics and the sciences. Thus, those whose academic career ends with the high school are better educated, while those who do go on are better prepared for university work.

Recommendations

The whole question of training for professional geologists and engineers is inseparable from that of the training for geophysicists. Your Committee, therefore, is in the position of being unable to confine itself solely to recommendations for geophysical curricula, but is under the necessity of including academic preparation for geology, and for those branches of engineering dealing with the extraction of mineral resources. A student is not fitted for university preparation in geophysics unless his educational background is such as to prepare him for further work in *either* geology, geophysics, or certain phases of engineering. Your Committee therefore recommends that:

1. Careful consideration be given to the curriculum outlined in Table 2, by those high schools sincerely desirous of providing a sound and adequate educational background for the students capable of assimilating the suggested material and who show aptitude for scientific or technological subjects.

2. Those universities whose aim is to provide a basic training for professional work in earth sciences and mineral industries, including geology, geophysics, and the pertinent phases of engineering, should adopt a curriculum essentially conformable to those given in Tables 1 and 2, and insist that no students be admitted thereto who lack the prerequisite educational preparation.

WRITTEN DISCUSSION

W. M. Aikin,* Montclair, N. J.—There are two aspects of the Committee's proposal upon

* Chairman, Commission on the Relation of School and College Progressive Education Association.

which I can comment in the light of my experience as director of the work of the Commission on the Relation of School and College.

First, it is clear, I think, that we have carried the division of labor even in the intellectual field to such an extent that many of the larger values are being lost. It would seem to me, therefore, that your proposal to break down the sharply dividing departmental lines is sound. We must somehow learn to work together more effectively and to draw upon any specialized field that has a contribution to make to a clear-cut purpose.

Second, while the student is in high school and in the lower division of college, his capacities, aptitudes, and interests should be more fully known and carefully studied. Upon the basis of that information and study, he should be much more intelligently counseled. If by aptitude and interest he is a potential geophysicist, he should be counseled step by step as to the courses he should take in preparation. This should not be done so much through rigid curriculum prescription as through personal guidance.

I heartily approve of the emphasis upon a broad cultural and social background. At the center of that, there should be in high school and college the kind of experience in the classroom and out of it that leads the students into an understanding and appreciation of the kind of life in which we as a people believe and a devotion to the service of that ideal.

C. H. Behre, Jr.,* New York, N. Y.—Footnote 2 requires further comment. All of the work that the American Association of Petroleum Geologists and the American Petroleum Institute have been doing on the genesis of petroleum and its relation to biologic processes emphasizes the importance of biology; also the detailed study of coal origins and the recent tremendous emphasis on bacteria as causes for sedimentary sulphur, iron and manganese ores. If, as petroleum geologists hope, the search for oil is to be facilitated by analyses of organic emanations above oil fields, geochemists will need to know not only the necessary minimum of chemistry to make adequate analyses, but also considerable about life processes, decay, and the like, to furnish essential background.

* Professor of Geology, Columbia University.

It is also to be hoped that people who go into geophysics, whether practical or theoretical, will be expected to do at least some graduate work. In response to the demand voiced by all leading petroleum and mining companies when adding young geologists to their staffs, virtually all first rate institutions have given up the expectation of training men for petroleum geology or mining geology without requiring at least some graduate study, and a bachelor's degree will be increasingly inadequate as time goes on. Theoretical physicists and theoretical geologists, not to mention geochemists, almost always have a doctorate if they go far. The Committee would be wise in indicating as much and in implying that it is at present only quoting the *very minimum* of requirements.

W. R. Chedsey, Golden, Colo.—I agree that the nation's entire high school program, and, for that matter, grade school program, needs overhauling. In the past 20 years a group of professional educators has dominated public school education with the idea that little Johnny must have his individuality developed, so in the attempt to give more individual attention to children to find out what their individualities may develop into, public school education has become very largely an entertainment course, with little or none of the drill or discipline on subjects such as English, Math, the Sciences and Foreign Languages, where taught at all.

These educators say it gives a better over-all terminal education to the great mass of students who do not go on to college. I cannot agree, and I think this report should be of considerable help to those who are now working on corrective programs.

H. G. Doll,* Houston, Texas.—Experience in our company has shown that we need not only engineers who combine a thorough knowledge of geology and theoretical chemistry and physics, so as to plan and use geophysical methods, but also we need engineers to design the equipment. A well-designed apparatus requires the skill of a good engineer to arrange the parts so that the complete apparatus will satisfy the theoretical requirements that have been established by the physicist, and so that these same parts will be easy to build; that

* Schlumberger Well Surveying Corporation.

is, to machine and yet rugged enough for field work. It seems to me that this type of engineer, who in France is typically represented by the engineers who graduate from the "Arts et Métiers" schools, is very difficult to find here. Engineers from this school have a very thorough training in machine work, drafting and the practical side of engineering. Most of the engineers in this country have a fairly good theoretical background and a very good training in the particular field they have chosen, but they have very little experience in drafting and machine design. On the other hand, even the best draftsmen have very little theoretical background and it is difficult for them to fully collaborate with the engineers and geophysicists in the designing work. There is a definite need for the type of man whose training combines both drafting and a thorough background in all branches of the engineering science. Without this type of man, designing must be done by cooperation between the physicists, who will unconsciously introduce numerous impractical difficulties in the building of the apparatus, and a draftsman, who will either fail to see these difficulties or be unable to distinguish between the ones that are necessary and the ones that are caused only by the lack of practical experience in designing.

Probably the man I am seeking to describe is most nearly represented by the mechanical engineer. However, even this engineer does not seem to have a wide enough knowledge of other branches, such as electricity, so that he can fulfill the exact requirements of a geophysical company. Consequently, the mechanical engineer functions more or less as a draftsman along the lines described above and such additional knowledge as he may have is more or less wasted.

S. F. KELLY,* Wilmington, Del.—The comments made by H. G. Doll introduce a new and interesting viewpoint, one that well may bear fruit in future modifications of geophysics curricula. There is a possibility that further investigation along the lines sketched in his comments may reveal the advisability of setting up different geophysics curricula for men desiring to specialize in research, as distinguished from those whose interest lies in field work. The former will require a far more thorough grounding in the theoretical aspects of the science. Field men should know enough of the basic theories to comprehend the significance of what they are doing but they will need a better preparation in field methods, management and repair of equipment, etc., than the research men. Perhaps two different curricula in geophysics are going to be needed, according to the objectives of the students.

A. F. GREAVES-WALKER,* Raleigh, N. C.—I am in entire agreement with the conclusions and recommendations of the Geophysics Education Committee. Having had considerable work in geology, I have always been convinced that geologists should have the same fundamental training as engineers, and I believe such training is even more important for geophysicists. The list of suggested courses in Table 2 is almost identical with our curriculum in geological engineering, which grew out of a curriculum in mining engineering which I established.

I realize that it takes more than mere agreement to obtain radical changes in curricula. It may be especially difficult to obtain the recommended changes in liberal arts institutions. I particularly like the recommendations on the content of humanities and English, but on these it may be difficult to get agreement among the engineering educators, as there still appear to be many who consider it a waste to spend much time on these subjects.

W. B. HEROY,† Houston, Texas.—I am thoroughly in accord with the position concerning better preparation for college. Any student who seeks to enter courses in applied science should be a superior student, able to carry the larger amount of work and the more advanced studies of the preparatory period outlined. A young man who had received the preparation outlined should have been taught to think along scientific lines and should be thoroughly prepared either for more highly specialized studies or to enter practical work.

Some thought might be given to the study of Spanish as a tool subject. It seems likely

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† President, Pilgrim Exploration Co.

that much of the employment of geophysicists will be in Latin America and that a working knowledge of Spanish gained in preparatory school might be desirable.

Mention is made of the desirability of a course in organic chemistry. This would hardly seem essential for the training of a geophysicist, especially in undergraduate years, and I suspect that someone has in mind the possibilities of geochemistry—scarcely germane to the discussion.

W. O. HOTCHKISS,* Troy, N. Y.—The one criticism I have to make is that the report considers what may be regarded as an ideal to approach. The course is based on the desirability of having all applicable knowledge. It fails to consider the time element in the student's life in college. No student has the time to do everything desirable. There is not time for this in the years he can devote to training. Many of the things in this outline must necessarily be left for the student to accomplish after his formal education is over.

W. C. KRUMBEIN,† Chicago, Ill.—I should like to have the suggestion that the geology department take the initiative in setting up the curriculum given the prominence it deserves. A discussion of the pros and cons of the issue would be helpful, as any administrators who may be interested in the report can act more intelligently if they are aware of the several factors involved in such an issue.

I am particularly pleased with the reference, near the end of the report, to the essential similarity between the basic training required by geologists, engineers, and geophysicists. If these three groups had the essential parts of such a curriculum in common, they would be much better able than at present to get together for the common solution of mutual problems.

J. B. MACELWANE, S. J.,‡ St. Louis, Mo.—The report as drafted represents much labor by the committee and especially by the chairman, S. F. Kelly, and I am sorry that I cannot concur with it as a whole.

In the first place, I disagree decidedly with the definition of geology (page 3) as *the* science of the earth. Geology was defined by Lyell: "Geology is the science which investigates the successive changes that have taken place in the organic and inorganic kingdoms of nature; it enquires into the causes of these changes, and the influence they have exerted in modifying the surface and external structure of our planet." (Principles of Geology, chap. I, Ed. 11, 1887, p. 1.)

It is, of course, *a* science of the earth and a very important one. It would be very unfortunate if it were to lose that significance by becoming merely a catch-all or generic term for *all the sciences* except astronomy and astrophysics. In its accepted traditional sense, geology is already a complex of intimately related sciences—physical geology, mineralogy, petrology and petrography, historical geology, stratigraphy and paleontology, physiography and geomorphology—so broad that no one man can hope to become expert in them all. Why encumber it with sciences only remotely related and for which a different type of training and experience is needed?

In the second place, I disagree with the statement on page 3 that "any curriculum in geophysics necessarily constitutes an important part of a curriculum in geology and should ideally be directed by the latter department." Must such a sop be thrown to professional jealousy? Can our committee not rise above emotionalism and wishful thinking and state the possibilities objectively for departments of geology as they exist today, as is done on the same page for the departments of physics and engineering? As correctly stated on page 2, the definition of geophysics adopted for the purpose of the report "embraces those geophysical sciences which furnish data whose utilization for the purposes of discovering mineral bodies of economic value constitutes the art of geophysical prospecting." The definition obviously does not embrace *all* the geophysical sciences. Nor is it correct to say that *all* geophysics is mainly applied physics any more than astrophysics and astronomy are applied physics. Only geophysical prospecting is applied physics in the sense of engineering. It is not true of volcanology or dynamic meteorology, or seismology, or geomagnetism, or geoelectricity, in themselves as sciences. The field of geophysics is so broad that no one can be an expert

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in all its branches. Include all this ideally under geology? To me the suggestion is absurd.

Thirdly, I would delete the sentence: "There should be nothing to prevent the eventual amalgamation of the departments of geology and geophysics." For those phases of the geophysical sciences that fall under the definition adopted in the report there would be much to lose and little to gain by such amalgamation and the rest of the geophysical sciences have no more place in a department of geology than has physics. The background, outlook, atmosphere and methods of the geophysical sciences, as well as their immediate subject matter, are different from those of the geological sciences. On the other hand, there should be the closest possible cooperation between the departments of physics, geophysics and geology. Nor should interdepartmental jealousies ever be allowed to interfere with such cooperation.

Fourthly, I think that in putting forth Table 1 we are defeating our purpose as stated on page 4: "First, the undergraduate course of study must be sufficiently broad and theoretical to permit a student to enter one of the several specialized fields in his graduate years. Secondly, it must furnish the undergraduate with sufficient knowledge of geophysical science to enable him to assimilate rapidly and intelligently the various specialized techniques of the art of geophysical prospecting should he choose, as so many will, to accept immediate employment in the industry." No *one* "course in earth physics and earth chemistry" can do either of the things the report rightly demands. Nothing short of 12 to 15 semester hours of solid geophysics based on previous courses in mathematics, physics, chemistry and geology will do it. Table 1 will never make an undergraduate *geophysicist*.

With Table 2 and the paragraphs that follow, I cannot concur at all. It is engineering gone wild. Having had the privilege of a thorough classical, philosophical and scientific education myself, I cannot take the position of recommending that pressure be exerted to prevent others from enjoying its satisfactions and its usefulness. Why make educational fools of ourselves and thereby defeat also our sensible recommendations?

S. F. Kelly.—Father Macelwane's discussion of the Committee report is particularly welcome, because it brings up some points that may need further elucidation and clarification. Unfortunately, it was not possible to compile a report that would meet the unanimous approval of the Committee members, but since the one presented met with the approval of a majority of the Committee, there seemed to be no way in which Father Macelwane's minority dissent could be used to modify the recommendations submitted.

Questions of definition may, on occasion, be ticklish ones, especially when the definition adopted must be used to circumscribe a science whose boundaries, per se, are vague. Etymologically we are correct in saying that geology is the science of the earth, since the word itself is derived from two Greek words meaning earth and discourse (science). The Oxford dictionary gives the above derivation and says that the word was used in medieval Latin, perhaps for the first time, in the 14th century by Richard de Bury in the peculiar sense "science of earthly things," applied to the study of law as distinguished from the arts and sciences which are "concerned with the works of God." The use of the word as a name for a distinct branch of physical science occurs first in English at a later date. This dictionary gives as obsolete a definition of geology as "the science which treats of the earth in general." It then proceeds to define geology as "the science which has for its object the investigation of the earth's crust, of the strata which enter into its composition, with their mutual relationships, and of the successive changes to which their present condition and positions are due."

This definition of geology is probably too restrictive to be accepted by most practitioners of the science, since it would exclude paleontology, or any study of the earth's interior or of its fluid envelopes of water and air. The Encyclopedia Britannica, in its 1941 edition, gives a broader picture of the scope of this science. It says: "Geology, in the broadest sense, has for its object the elucidation of the history of the earth and its living inhabitants. For practical purposes, however, it is necessary to adopt somewhat arbitrary limitations. The earliest stages in the development of the earth belong to astronomy and cosmogony, whereas, at the other end of the scale, geology in some of its aspects merges into history and geog-

raphy, as well as into the biological sciences, including anthropology and ethnology." The article then goes on to say that geology "studies the development of the physical features of the earth, the composition and structure of the rocks composing it, and the evolution of plants and animals from their unknown beginnings." Here again, the hydrosphere and atmosphere seem to be eliminated (although the author does discuss them in his article), an omission upon which geologists probably will be divided. The introductory sentences, however, certainly sound as though the author were speaking of the "science of the earth." It is interesting to observe that Doubleday's Encyclopedia, 1931, says: "The word geology means literally 'a discourse on the earth' or 'the science of the earth.' "

There is evidently a disagreement among encyclopedia authorities as to the exact definition of the science of geology. Under such circumstances, disagreements may be expected among the geologists themselves, and the best we can do is to try to arrive at a compromise definition.

Possibly Father Macelwane's unwillingness to accept geology as the science of the earth arises from his conception of what is meant by the "earth." Can we not agree that the term covers the material, inanimate components of our globe and its fluid envelopes, and the animate inhabitants only in so far as their remains, or the records of their activities, are preserved in the inanimate constituents? Thus, we include fossils, and the products of such biological processes as those connected with the origins of coal, petroleum and some sulphur, iron and manganese deposits, etc. By such a definition, the "earth" includes the lithosphere, hydrosphere, and atmosphere, and the biosphere in so far as it becomes part of or modifies the other spheres, principally the lithosphere.

If we can agree on this definition, "the science of the earth" will naturally not include such things as psychology or sociology, and it cannot include physics and chemistry because they are fundamental to geology, which is a science of the second order of dependency [M. King Hubbert: The Place of Geophysics in a Department of Geology. *Trans.* A.I.M.E. (1941), 138, 38]. If geology, as the science of the earth, concerns itself with the study of the lithosphere, the hydrosphere, the atmosphere, and restricted aspects of the biosphere, then geophysics, which studies the physical and chemical relationships within and of these spheres, is certainly a part of the broader science of geology (or vice versa?).

In commenting on our definition of geophysics, I think Father Macelwane has misread the explicit statements made in the report. He says that the definition adopted "does not embrace *all* geophysical sciences." He evidently draws this conclusion from a part of the statement which says that "this definition embraces those geophysical sciences that furnish data whose utilization for the purposes of discovering mineral bodies of economic value constitutes the art of geophysical prospecting." That statement means exactly what it says—that the art of geophysical prospecting is embraced in the broader definition of geophysics, which we go on to say is "broad enough to include various branches of the physics of the earth." The definition was certainly intended to embrace *all* the geophysical sciences.

Father Macelwane further contends that it is not correct "to say that *all* geophysics is mainly applied physics," and that "only geophysical prospecting is applied physics in the sense of engineering." The report definitely does *not* say that geophysics is mainly applied physics, nor that it is applied physics in the sense of engineering. The report uses the expression "the integrated application of the disciplines of physics, chemistry and geology, to the solution of problems involving the materials of our earth . . . " The application of physics to the solution of any problems is still an application, whether it be in the engineering sense or in the sense of studying problems in other fields of "pure" science. Both senses, therefore, are covered by our definition.

There can be no quarrel with Father Macelwane's contention that the courses outlined in Table 1 are not adequate to make an undergraduate geophysicist. The report itself emphasizes that point. It is merely a question of practical university administration in setting the point at which undergraduate work will cease and a man will receive his degree. Since our universities are committed to a four-year curriculum, we did the best we could in recommending studies that would at least give a student the fundamentals, and a perspective of the applications. If he has to leave college

at the end of four years, he will at least be in a position to assimilate intelligently the additional knowledge required in whatever specialized field he takes employment.

Acutely aware of the deficiencies of Table 1, it seemed to us that some of them could be remedied by requiring a more rigorous preparation in high school. This would permit more advanced courses in the college curriculum. There is no intention on the part of the Committee to decry the value of the classical and philosophical phases of a broad education. Nevertheless, if a man envisages only four years in college, it is evident that he must sacrifice either some courses of a broad cultural character or some courses needed to complete his breadwinning capacity. Dean W. B. Donham, of the Harvard Business School, has said that "Preparation for life must include preparation for making a living, for without this capacity self-respect ceases." The balance that must be struck will have to be decided by the student himself, and by the authorities of the institutions he attends. Table 2 specifically refrains from indicating the relative time emphasis to be placed upon the courses recommended, and provides for electives, which should be devoted to the "classical and philosophical phases of a sound education."

D. C. McCann,* Houston, Texas.—The idea of teaching the more advanced phases of the sciences in high school is good. Unfortunately, judging from some teaching experience several years ago, it is my opinion that the average high-school instructor does not have a sufficient background to be able to teach the science courses that now are given in the first year or two of college work. Consequently, the program outlined for the high schools would probably lead to a study and revision of the courses necessary for the instructors, and this becomes complicated indeed. Therefore, whether we like it or not, it will be necessary to use the instructors and facilities of the colleges and universities as long as the requirements and facilities of our secondary schools remain as they are today.

L. L. Nettleton,† Pittsburgh, Pa.—It is my feeling that there is more weakness and room for improvement in the high school or preparatory training than in the college work, but the difficulties of getting the kind of high school training that we would like to see are much greater than are possible revisions of college schedules. Apparently, science training in high schools is trending backward or downward rather than the reverse, under the pressure of designing high school training more for the large majority who do not go on to college rather than the small minority who do. With regard to training in physics, this development has been plainly set forth with some rather shocking statistics, which are given, for instance, in a note by M. H. Trytten in *Science* for Oct. 24, 1941, which is condensed from a longer article by Trytten and Leach in the *American Journal of Physics* for March 1941. These papers contain material pertinent to any discussion of science training in secondary schools.

* Schlumberger Well Surveying Corporation.
† Gulf Research and Development Co.

W. R. Teeters,* St. Louis, Mo.—The role that secondary education is to play as set up in Table 2 is being met in our schools. We offer all courses suggested in this table. The brighter students avail themselves of these offerings. Few of the students of lower abilities are to be found in such courses. However, we do offer these less technically minded students plenty of science involving physics, chemistry, biology, physiography, etc. on a lower level, generally in the form of orientation courses of a general nature.

In school systems where the enrollment is not large, where chemistry is taught one year, physics the next, it would be impossible to follow your Committee's suggestions. In the smaller communities, where money is always a problem, often physics and chemistry are omitted because of cost. Further, it would be costly to carry out the program of mathematics, for the same reason. It is costly to have a class for two or three students, as most certainly would be necessary for college algebra or trigonometry in small communities. The total student output of small communities is greater than the total output of large cities.

To sum up briefly, your Committee recommended a plan that would function in large schools but could not be carried out completely

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in the smaller ones. However, I am in complete accord with the underlying philosophy of your Committee's recommendations, especially that principle of thoroughness, which the schools of America must foster if our nation is to survive.

W. T. THOM, JR.,* Princeton, N. J.—I have given particular attention to Table 2. To me, this is the highly important part of the report, since it gives much needed emphasis to the matter of proper pre-college training for men who have professional and scientific aspirations. It will be very helpful to be able to quote the A.I.M.E. along this line, and this quotation should do much to clear up the present unsatisfactory situation.

ORAL DISCUSSION

A. C. LANE, Cambridge, Mass.—I wonder how many of us have had any course like that exemplified for us.

I happen to have with me a letter, twice censored, from Germany, discussing a certain problem in the Alps. I think it may be classed as geophysics. The author is discussing the flow of heat through the tunnels that go through the Alps. It is a rather interesting theory. In the first place, he comes to the conclusion that the flow of heat is twice that which Bullitt and Bennett have found for England, for instance, and that this may be due to an extra thickness of "sial," otherwise known as granite, which is more radioactive than the average rocks. In that problem he compares the gravitative anomalies under the Alps, certain seismic effects, the geothermal gradient, plus the activity of the rocks and the radioactivity of granite; all those factors come in in the proposition.

I have lived so long that I know that my education will never be finished until my life is finished, and I am inclined to think the same about the education of the geophysicist in general. If we can teach the students so that they will understand the language of the papers, we will do mighty well.

S. F. KELLY.—The question was raised by someone this afternoon of the student's equity in a four-year degree. I think that "equity" falls in the classification of the preconecived academic straitjacket.

Why should the student have an equity in a four-year degree? Why should the colleges insist on the present semester arrangement of their courses? Why should the students in a university take two or three months vacation every summer? Why can't the universities set up requirements that more or less fit the program their graduates are going to meet when they go into industry? You do not get two or three months vacation when you go to work. You are lucky if you get two weeks. If you are working for somebody else you get that much, and none if you are working for yourself.

Why can't the universities set up a three-semester, or four-term or three-term curriculum, and give the students the same amount of work in two or three years that now they get in four? That might produce an equity in a two-year or three-year degree. Why do we have to stick to a university program which, according to Dean W. B. Donham, of the Harvard Business School, was predicated originally on the agricultural economy of this country, when the students were given long summer vacations so they could work on the farm. How many students are there nowadays who have to work on the farm in the summer time?

It seems to me that we should get away from not the horse and buggy but the horse and plow conception of university education.

A. C. LANE.—That expression, "equity in a college degree," arouses my curiosity. I wonder if that has anything to do with the fact that often the holding of a degree of a certain kind is a very distinct advantage in applying for positions, or even lieutenancies in the Army.

To illustrate, years ago one of my students, I happen to know, passed the best examination for a position on the Geological Survey of the United States. Incidentally, he is now working for it. But he did not get a position at that time because in the Tufts' College catalogue geology was not recognized as a major subject. It was recognized the next year! I always had preferred, up to that time, to have my students register major in physics or chemistry, but I learned that to have geology a major subject in the catalogue had its equity value in cash.

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* Blair Professor of Geology, Princeton University.

S. F. KELLY.—That is one way of getting the university to do what is needed, put a cash value on the type of program desired.

G. W. NOBLE,* Rolla, Mo.—Has Mr. Kelly any plan to help the technical schools combat the tendency toward progressive lowering of scholastic standards of high school graduates? In Missouri, as in many other states, all state-supported colleges and technical schools are required to admit all graduates of high schools within the state. In practice, it is usually impractical to impose entrance conditions on students with certificates from high schools in our own state. Less than half of our high school students enter college, and there is a tendency to substitute what might be termed "finishing school courses" for basic foundation for college or technical training.

As to the question of speeding up: The real question is whether we can profitably speed up the educational process. Unless we can speed up the mental maturity of the student, an accelerated educational program is very apt to fail. You cannot make an oak tree grow from acorn to full height in two years because you turn on extra light at night; it takes time.

S. F. KELLY.—I was very much interested in the paper read by Dean Pouliot, of Laval University, at the session last night. He mentioned that the students entering Laval University had formerly been very deficient in mathematics, but that now Laval University has placed its mathematics requirements for entrance at such a level that freshmen take differential and integral calculus. If Laval can do this in Quebec, why cannot the universities in this country do likewise?

Mr. Noble asks whether I have a formula for doing it? No, I have not. I am not an academic administrator, and must leave the problem to others. I am merely emphasizing the objective to be attained, and if the men active in the academic field agree with that objective, they are the ones who should be able to find the means of achieving it.

It seems to me that a high school system that reduces the level of its education on the grounds that most of its students are not going on to college is absolutely betraying the trust it carries for the education of the youth of this country. The movement should be in the reverse direction, to give the students *better* education and *better* instruction in the high school, for the very reason that their academic instruction will cease with that stage.

Possibly a division of the educational stream, even at the high school level, is desirable. Students who are going on to university work presumably have a higher mental capacity than the students who are not. They should therefore be given instruction along more advanced and theoretical lines. The students not going to college could conceivably follow lines of training oriented toward the arts and crafts, or vocational work, but they should very definitely receive some instruction in the sciences now so fundamental in all our activities —physics, chemistry, biology and sociology. Students planning to follow scientific or engineering courses in college should get advanced mathematics and sciences in high school that will enable them to profit far more greatly from their college education than is possible with the present high school curricula.

H. W. STRALEY, III., Waco, Texas.—I believe that numbers of high schools offer the courses suggested in Table 2. For example, night before last I dined with a graduate of Fort Wayne High School who had studied physics, chemistry, drafting, college algebra and trigonometry.

W. H. BUCHER,* New York, N. Y.—If you are looking toward a radical revision of the mathematics and science training in high schools and need convincing proof that a thorough and coherent course can be developed, I suggest that you make a study of the equivalent of the science course of the high schools in the Swiss educational system. Unless I am much mistaken, there the students in their last year—that is, when they are between 17 and 18 years of age—get an elementary course in differential and integral calculus. It can be done.

The real question is, as Dr. Noble suggested, how are you going to get it done? You will be asked how many geophysicists this country needs or can support. As long as the engineering

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colleges do not protest against the present schooling and the liberal arts faculties resist any changes, can you hope to press a demand based on the needs, say, of 70 men? I am afraid we shall pay a heavy price in this war for our past indifference in the matter of mathematical and physical training of the average citizen, not to speak of the specialist. But I fear that even so the revision you suggest will long remain far distant.

Fortunately, we need not wait for that day for our supply of young geophysicists. Several of the best young geophysicists started as students of physics and graduated in it and became interested in geology only late in their student days. Men with a sound theoretical physical background step easily into geophysics. There seems to me to be our hope for the immediate future.

The situation is parallel to that of biophysics. In that field for the time being there are no financial inducements. Consequently we hear little about the need of special training for biophysicists. A man who wants to be a good biophysicist has to be first a good physicist. If he becomes interested in the physical phases of biology he has little difficulty in stepping into it and doing beautiful things.

I am inclined to believe that the cause of geophysics would best be served if all the sciences combined in a drive for a coherent and thorough schooling in the fundamentals of mathematics, physics, and chemistry comparable to that considered basic for all engineering training.

R. L. Sackett, New York, N. Y.—It is characteristic of us, and we have been at it for 25 or 50 years, that we criticize the preparation the high school provides. What have we accomplished in the meantime? Practically nothing.

The present trend, and that of the last five years especially, has been toward vocational training in the remoter parts of the country; that is, the small towns. The large cities have retained their technical high schools and their technical curriculum. However, by and large, our students in engineering, geophysics and geology are coming from schools that have been tending, and are tending more and more, toward trade and vocational training.

If you intend seriously to meet the situation, it is necessary that unified pressure be brought to bear upon public school authorities and the National Educational Association. A lack of mutual understanding of high school and college problems is partly responsible.

Large bodies move slowly; in other words, it is necessary that we accept a high school student with the preparation that he has at the present time. For a few years it seems inevitable that you cannot expect a readjustment in high school education. That bears upon the curriculum provided by the Committee. It means that real instruction in English, which has been in the four-year curriculum may be compressed into three. The instruction in English ought not thereby to be reduced in quality or quantity.

Some of the speakers have emphasized the fundamentals. I think we all agree that they constitute the foundation, and that we need not put too much weight upon the steeple until we have agreed upon what we call fundamentals. I question whether there would be such a large agreement among you if each were to write out his idea of what constituted the fundamental subjects.

In the curriculum I noticed a survey of the humanities and a survey of the social studies. I cannot help injecting my objection to that word "survey."

Two purposes are in mind, one to prepare the student to participate in the work of the geophysicist; the other to prepare the student to participate in other work than that of the geophysicist. Not all of them will be employed all the time in that field; and it is, therefore, necessary to see that a man's career, by and large, is under consideration, and to give him something more than just the "surveying." The time is passing when we can say, "Give him the fundamentals, the rest doesn't matter much." The "rest" is beginning to matter a good deal. The very fact that reference was made to the other studies—i.e., the social—is a realization that we are coming gradually to appreciate the fact that we are preparing the students not merely for a technical career, or a technique, but that we are trying to prepare them to live as well.

So, these subjects of sociology, and so forth, will increasingly receive attention from the technical fraternity. By and by we shall have something in the way of industrial psychology

and something in the way of industrial sociology. The probabilities are that some of these men here, or others like them, may contribute books on Social Science and Engineering. The engineer is a participant. There are new books out on industrial psychology and industrial economics, and they are done in the terms of engineering practice.

So we must keep our feet on the firm ground of fundamental principle, because we are preparing these young men for life as well as for a specialization.

A. F. BUDDINGTON,* Princeton, N. J.—I would like to consider myself one of those academic geologists at whom some of the barbs of the Committee have been directed. However, I really am under very deep gratitude to the Committee for the stimulus the report has given me, and I believe it has done a grand and necessary job in presenting the case for geophysics.

Some points have been raised that I should like to speak of; namely, what has been said by some of the others. It seems to me that a very grave step was taken in saying (p. 8) that no students should be admitted with a lack of prerequisite education.

Ideally, I agree completely with the report; practically, I think you would be cutting off a considerable number of the very best men, who might be potential candidates for courses in geophysics. Personally, I should much rather have the first grouper going into geophysics with some blanks than a third or fourth grouper who had had physics, chemistry and biology, and so forth, in high school so that he could enter this curriculum. It is a practical matter. Men are coming into the universities without those courses, some of the best men. You cut yourself off from them and I do not believe you are accomplishing your ultimate objective.

The other point is not serious. Several remarks have been made in this report and past reports on departmentalization. I cannot help feeling that the curriculum here is setting up another straightjacket department, this time for geophysics. After all, I think we must have a certain variety of curricula open even for geophysicists.

Another point raised is the matter of acceleration; some of us who are at the immediate moment connected with accelerated programs are not quite as enthusiastic as Mr. Kelly about running through the year and cutting out the summer vacation period. It raises a serious financial problem for many men. At present, many men work during the summer in order to enable them to return to the university for the other two seasons. It means that the universities must raise more scholarship funds somewhere if they are going to operate on the yearly basis.

Furthermore, I can only second the point that was raised by one of the previous speakers, that of maturity. You cannot force the feeding too fast. It does take time for it to sink in and be digested. And I think the proposal to make a five-year course rather than to try to speed up and jam everything into a shorter time, is the better one.

S. F. KELLY.—With reference to your return barb on the subject of departmentalization, you will notice we say that a department of geophysics could have its own staff while maintaining a close liaison with those other departments to which its students go for some of their foundation training. There must be cooperation between the departments; it is the lack of such cooperation, not departmentalization per se, at which we are shooting.

Certainly, it is desirable to have some variety in the curricula open to geophysicists. In studying the matter, however, we found that the fundamentals necessary for almost any geophysical curriculum would take virtually all the time of an undergraduate course. The variety, therefore, has to come in the graduate years. Modifications and changes undoubtedly will be needed for particular cases and particular institutions, but essentially the course we suggested presents the minimum requirements of fundamentals. To the extent that insistence upon a sound fundamental basis imposes a straightjacket, then that is what we are attempting.

In justice to the profession, to the university's reputation, and to the student himself, the standards of such a curriculum must be upheld. Students deficient in prerequisites, who are nevertheless capable of assimilating the work, might conceivably be admitted. For the benefit of all concerned, however, the stress should be upon requiring candidates for the

* Professor of Geology, Princeton University.

proposed course to make up their deficiencies, either before enrollment or while taking the work suggested.

As to the speed-up versus the four-year or five-year course, I call your attention to the following points: If a man attends a university for nine months of the year, and then works three months in the summer time he completes his course in four years. If the educational setup is changed to a basis of four terms per year, so that he completes four years of work in two years, the man is still at liberty to take one term of vacation to work. If he takes two terms of vacation to work, and comes to school for the other two terms, he will still get his degree in four years. There will be absolutely no difference between that arrangement and the traditional one now followed. The student who is financially able to go through without working, however, will be able to get his degree in two years

Relative to your comment, Professor Bucher, that we might have difficulty in advocating the stiffening of the high school course merely because we need geophysicists, I would call your attention to the last page of the report, in which we say that the whole question of training for professional geologists and engineers is inseparable from that of the training for geophysicists. If it were not that, as a committee of the American Institute of Mining and Metallurgical Engineers, we were confining our attention to the mineral industries, I would go further and say that the curriculum we have recommended for high school and college is applicable not only to the educational preparation of geophysicists, geologists and mining engineers, but in large part to the academic preparation desirable for most of the engineering professions.

W. A. STAAB,* Morgantown, W. Va —Suppose there were a curriculum arranged as suggested in the report, and this curriculum interested some 100 or 200 young men each year. After they have gone through this training, what expectancy do they have that they can earn a living and make geophysics their life work? That is one question I would like to have answered.

Then, to answer the remark that it would make no difference whether the average university ran these students through in two years or four years, I want to say that it makes a lot of difference, because the average university would probably have to increase its staff by at least 50 per cent in order to do that. Many professional courses are given only at one time during the year and at the present time the staff is not large enough to give those courses every semester, which would be necessary under your new system.

* School of Mines, West Virginia University.

S. F. KELLY.—Thank you for bringing up some of the practical points that militate against adoption of some of these suggestions. I quite realize that there may be a good many objections which would make it difficult to put our recommendations into practice.

Your question as to probable opportunities in the field of geophysics was taken up in the report of the Committee issued in 1940. There may be mimeographed copies of that report available at the headquarters of the Institute, and it is summarized in the 1940 volume of Geophysics, A.I.M.E. TRANSACTIONS, volume 138.

From questionnaires, we arrived at the conclusion that the absorptive capacity of the industry was in the neighborhood of 65 men per year. Information that came to me after that had been published led me to believe that we were far too low; that it might be double that figure. That was the status of geophysics as of two years ago, ignoring the fact that undoubtedly there will be a broad expansion, not only in geophysical prospecting but in the branches of geophysics dealing with other physical phenomena of the earth. As an illustration, consider the subject of meteorology, which has undergone a tremendous expansion in the past few years, owing to the demand by the airlines for trained meteorologists. As things are going now, the absorptive capacity of the industry might well be 100 or 200 a year, and we hope it will grow.

J. W. PEOPLES,* Washington, D. C.—I should like to repreat a point I have made in correspondence with the Committee, and one that has been suggested by other speakers today: I do not see the necessity that all geologists or all geophysicists should have the same training and background. The needs are

* Formerly Associate Professor of Geology, Wesleyan University.

too broad to be covered completely by one person. Therefore, it seems desirable to me to have geologists and geophysicists who have emphasized different phases of their training.

H. W. Straley, III.—The liberal arts college should offer two beginning courses. Most of its beginners seek solely to satisfy science requirements. In my institution, I have a course specifically for this group, to which I do not admit science majors. The latter group takes a special beginning course based upon prerequisites in chemistry, physics, and mathematics.

S. F. Kelly.—There can be no quarrel with J. W. Peoples' contention that the needs of geologists and geophysicists are too broad to be adequately met by any one curriculum. For example, those desiring some knowledge of geology or of geophysics merely as a cultural subject certainly have no use for the courses we have outlined. We are not concerning ourselves in any way with that aspect of the problem, but are confining ourselves solely to the needs of *professional* geophysicists. For most of them, the essential fundamentals will be the same, but even here, some changes and modifications will undoubtedly be required in the setup we have proposed. Time and experience will show what these will be; the proposed curriculum is not offered as the final word, but as a basis upon which to work, and eventually to build curricula better suited to meet the varying needs of the professions of geology and geophysics.

Geophysical Education

By Donald C. Bradford*

(New York Meeting, February 1942)

The place of geophysics in the curriculum of a college or an engineering school has been much discussed. There is uncertainty as to whether the graduate may be called a "geological geophysicist" or a "geophysical geologist." Some have used the term "geophysical engineer." The question of the specialized undergraduate curriculum versus a general undergraduate training in the parent sciences with the addition of cultural electives has been and is still being argued.

The literature during the past 10 years shows that there are two rather definite schools of thought on this subject. The prospective employer, engaged in active geophysical exploration, visualizes the graduate in terms of the routine work he will do in the field. The school administrator, grounded in many years of tradition in the cultural type of education, visualizes the graduate in terms of his position in a political and cultural society as well as in his work as a professional geophysicist. Both are right and both wrong. A third school of thought, that of the student himself, has been almost totally ignored.

It would seem best, for the purpose of this paper, to treat these various points and allied material separately, and then to integrate the conclusions as a set of conditions that should be fulfilled as far as possible in the ideal curriculum. At the end the relationship of our findings to the curriculum that has been tentatively adopted at the University of Pittsburgh will be considered.

Divisions in Definition of Field of Geophysics

Geophysics is that field of science in which geological and earth problems are solved with the use of physical and chemical techniques. Altogether too much attention has been paid to the artificial separation in this science of the commercial applications from the so-called "pure" or academic geophysics. The only real difference in the two types of work is one of scale of operations. In the commercial field the scale is large in terms of financial backing, immediate economic importance, and speed of operations. In the academic field the scale is large in terms of breadth of interests, in eventual economic importance, and length of time allowable for theoretical investigations. In exploration work the scale is small in terms of dimensions, since the methods are applicable only to the outer 20,000 ft. or so of the earth's crust. In academic work, the student is not pressed for results of immediate economic importance, and therefore can afford to spend more time on problems that seem unimportant at the time.

In the sense of background knowledge of the parent sciences necessary to the geophysicist, no essential difference can be found. Physics, chemistry, geology, and mathematics together, and in their proper proportionate amounts, form the matrix from which geophysical ideas and methods may spring.

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But before considering the problems relating to a proper geophysical curriculum, or its aims, let us touch for a moment on the future the student may face if he elects to enter this field.

Future of Geophysics

When we speak of the future of geophysics we should for the moment distinguish between geophysics in the broad sense, as outlined by the American Geophysical Union, and geophysics in the sense of exploration only. In the former sense it is obvious that the science of geophysics is as inherently immortal as is chemistry, physics, or any of the other basic sciences. No one of these sciences will cease to exist until the whole of man's ignorance concerning his environment is dissipated. The writer assumes that those who felt in 1940 (as indicated in the Committee Report[1]) that the future of geophysics was only fair or poor were thinking in terms of the methods of exploration for natural resources known at that time.

If chemists of 50 years ago had felt that the science of chemistry would perish when all the problems of quantitative analysis were solved, the situation would have been sad indeed. The only certainty about the future of any science is that sharp and sometimes rather artificial boundaries between it and other sciences are disappearing, and undoubtedly will continue to disappear. In a broad sense, the age of classification as the essence of a science is gone.

Pure physics and pure chemistry have had for many years two "in-laws" known as physical chemistry and chemical physics. Mathematics is applicable to all sciences. Biologists and bacteriologists are rapidly learning that the methods of physics, chemistry, and mathematics are necessary and integral parts of their work. Geologists are coming to the realization that rock classification and formation naming are no longer the whole of geology. They have at last become cognizant of the fact that, to quote Lord Kelvin,

> When you can measure what you are speaking about and express it in numbers, you know something about it, and when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely in your thought advanced to the stage of a science.

Thus mineralogy in itself, when it consisted of mere classification of hand specimens, was not a true science; but when it grew to include the field of optical mineralogy, in which the laws of physical optics are used, this tool of geology could be said to have graduated to the stage of a science.

Structural geology is slowly passing through the same stages of development. At first the geologist was interested only in the classification of the structural types and their location in space and time. Later, when he wished to correlate these findings with possible causes, and when the relationships between structures were sought, the geologist found that he must turn to those versed in the mathematics and physics pertinent to the problem, who could perform experimental work in that field, and who could express the results in numerical form. Thus tectonophysics was born.

These steps in the development of geophysical thought are presented not because the reader needs to be reminded of them but rather because no plea for interdepartmental cooperation in our educational institutions can be made too strongly or clearly. Sharp departmental boundaries are our inheritance from the age of classification, rather than of analysis, in science. The potency of the walls that have arisen between departments, apart from this inheritance, is the result of group rivalry and the natural human desire for individual

[1] Report of the Geophysics Courses Committee of the Mineral Industries Education Division, on the Integration of Geology, Physics, and Chemistry for the Solution of Earth Problems. A.I.M.E., New York Meeting, February 1940. Summary in *Trans.* A.I.M.E. (1940) **138**, 89.

recognition. One needs only to examine the catalogues of many universities to verify the considerable duplication of courses in different departments, with the inherent waste of money, time, and energy involved therein.

Many of the ideas presented here are not original. Others have said the same things or their equivalents. These points have been enumerated at the cost of possible repetition in order that some of the principles governing the formulation of the geophysical curriculum at the University of Pittsburgh may be understood.

Culture versus Educational Functionalism

Grouped under this topic are such questions as the following:

1. Should the college graduate in any professional field be forcibly exposed to a certain predetermined amount of the cultural subjects,* irrespective of his interests?

2. Should preparation for a profession in the undergraduate years be specific or general?

3. Is it possible to train a student for a profession in four years?

4. Is the nature of the history of geophysical activity at any one institution conducive to the formation of a well-balanced curriculum?

It is easily seen from the nature of the four questions outlined that these matters are not peculiar to the formulation of a geophysical curriculum. Periodicals are devoting an increasing number of pages to discussion as to whether or not culture is the correct end product of the educational process. The word "culture" is used here to represent mere refinement in taste and manners.

One definition of the word (Webster's International Dictionary, Unabridged) is as follows:

> Act of improving or developing by education, discipline, etc.; the training, disciplining, or refining of the moral and intellectual nature.

In the latter sense, the injection of culture into the prospective professional man is entirely fulfilled by any standard engineering school in the country. This view of culture is parallel with the thoughts of Wallace Brett Donham, Dean of the Harvard Business School, when he says:[2]

> We have heard much talk about the values of liberal education as preparation for life rather than for making a living; some of it wise, much of it rationalization and a defense of existing conditions. ***Too often we overlook the cultural value of being able to get a job and keep it.*** The collapse of old Germany was hastened by the inability of university-trained men to fit themselves into the economic life of the community. The long procession of college-trained men who have sought my help in getting jobs during the past ten years leaves the strong impression that in most instances cultural values fly out the window when men cannot earn a living. ***Preparation for life must include preparation for making a living, for without this capacity self-respect ceases.***

The writer feels that this practical conception should hold whether the United States is at war or at peace. It should become all the more important when war activities cease, and readjustment becomes increasingly painful during economic reconstruction.

Emphasis in Donham's remarks has indirectly been placed on the development of the individual with respect to the community or the state. Let us examine for a moment the individual himself. Many educators have expressed the belief that the greatest single cultural influence on an individual is the home. The writer would carry that idea even further. If, during the early formative years of the life of an individual, a refinement in taste and manners is neglected in the home, a later lifetime of exposure to cultural subjects

* By "cultural subjects" is meant such fields as history, philosophy literature, music, fine arts, and ociology.

[2] W. B. Donham: The College in a Changing World. *Harper's Magazine* (January 1942) 137.

will do little more than produce a deceptive veneer, harmful to the individual and irritating to his fellowmen. On the other hand, if home training during the formative years stresses those characteristics, the individual will seek those values of his own volition in later years, and will be better prepared to withstand keen competition by concentrating on his vocation while attending the university or college.

With these words the writer closes his case for the vocational type as against the liberal arts type of training. Even though the term "geophysics" has not been mentioned in this section, it is apparent that the tradition of culture in education must be considered in the building of a technical curriculum.

Specific versus General Undergraduate Training

We are here concerned with the trade-school approach to geophysics as a profession as compared with a well-rounded preliminary training in the fundamental sciences. Since much has been said already along these lines, more space will not be taken except to emphasize a point or two.

A "trade-school approach" may be defined as the training that prepares the student to perform certain special tasks at a semiprofessional level, but which does not enable him to do original work toward the advancement of that profession. Because of intense commercial competition in geophysical prospecting, the university instructor cannot give the student first-hand and completely modern information on techniques currently in use. Therefore, if the student learns methods that were in use 5 or 10 years ago, he is hopelessly handicapped when attempting to conform to the latest and most efficient methods. The employer would rather have a graduate trained in the fundamentals, since he assumes that the new employee must be given training in specific techniques.

Is Four Years of Training Sufficient or Only Minimum?

The answer to this question has been given many times. Professional requirements in all fields have been increasing rapidly as more and more specialized knowledge has accumulated. The need of an adequate knowledge of physics, mathematics, and geology by the geophysicist has been stressed. To obtain sufficiently intimate knowledge of these sciences so that the graduate can handle competently any one of the possible solutions of a geophysical problem requires all of four years. Each science has grown in the past 50 years to include techniques, facts, and literature that cannot be assimilated properly in less than four years.

It would indeed be difficult to include what may be called "tool" subjects with the proper amount of orthodox chemistry, physics, mathematics, and geology in four years and still fulfill the usual university requirements for the bachelor's degree. These tool subjects are:

1. English composition and report writing.
2. Drafting.
3. Surveying.
4. Machine-shop practice.
5. Hydraulics.
6. Strength of materials.
7. Geological field methods.
8. Business law.
9. Optical mineralogy.
10. Procedures in experimental physics.

Therefore, the optimum training period in geophysics would seem to be one of five or six years, with additional time for the advanced degrees. But, as one university administrator has so aptly put it, "The American student seems to have an equity in a four-year degree." This was shortly before the United States became embroiled in the present war. What the feeling will be now, or at any time in the next few years, is difficult to predict. Will

the new stress on results at the expense of social and extracurricular activities have a lasting effect on curricula or on time requirements? At the moment, the length of time spent in commercially unproductive school attendance is being decreased to two years and nine months. Could it be at all possible that for certain professions an increased amount of training might be included in four calendar years? The writer would be interested in comments on this matter.

In the light of the facts just discussed, it would seem that curriculum builders in geophysics have a rather narrow choice of alternatives. They may:

1. Increase the length of time required for a degree to five or even six years.

2. Drop all courses of the purely cultural type.

3. Work toward the ideal of complete interdepartmental cooperation, with the result that certain key routine courses in the basic sciences shall emphasize geophysical problems and methods more than is now customary.

At the present writing the third suggestion appears to be the most fruitful course to follow.

Training Subordinates

It has often been said by employers of geophysical technicians that they do not particularly wish a highly academic background in their employees. It is felt that, in a pinch, men with only a high-school training may be taught the fundamentals of a particular technique so as to fill a breach in the ranks.

It is the feeling of the writer that in the future the four-year graduate will never be more than a subordinate. Many are called, but few are chosen—this is true in all lines of endeavor. There will always be a number who physically, financially, or mentally will be unable to make the complete grade. Among them we should look for subordinates—subordinates who have their background at least in common with their more advanced superior.

Therefore, it would seem to be a fair conclusion that the college curriculum in geophysics should be designed to turn out a prospective graduate student. Those who have the ability will continue their studies. Those who are unfortunate will not have lost four years of time and effort. In this light the geophysical apprentice from the trade school has no real place in the picture.

The Indecision of Immaturity

Few students in their freshman year know exactly what they will wish to follow as a career in later life. Some enter school as engineers and graduate as pure scientists. Some may even graduate as liberal arts majors. A few have gone as far as three years in liberal arts or business administration and then have decided to become engineers, even at the expense of a year of additional work.

There is no real way of predicting these changes in attitude, for the reasons behind them are unknown functions of the mental attitude and daily contacts of the student. Furthermore, at the age at which the student usually finds himself in a college or university, between the limits of 18 to 23 years, he has neither a constant attitude toward life nor a conception of what the world has to offer him. These are the years during which a chance visit to a factory or an unexpected hour of personal contact with an interesting faculty member may change his entire outlook and ambition.

Therefore, if we guide the student into trade-school geophysics, or into a curriculum that stamps him indelibly as a geophysicist and nothing else, more harm than good may result. Few of us now in geophysics ever actually studied geophysics as a set curriculum. But if we had not been given a well-rounded and basic scientific background we would not have been able to change to geophysics. The same logic

holds in the case of the geophysics major. He will not necessarily become a geophysicist. Therefore, any curriculum in geophysics should contain background insurance that the graduate will be able to handle himself, *and to make a living*, in some allied field of endeavor.

Earth Sciences at the University of Pittsburgh

All of the preceding sections of this paper have been based on the assumption that a geophysical curriculum will operate under the direction of a college or school of a university, rather than as a separate unit. Thus there are always additional requirements to be met, including those of the profession. Again, since in most schools geophysical activities began through the interest of some individual in a nongeophysical department, it is often necessary to consider the local history of geophysical activities, and also the history, interests, and personnel of the school unit at present in charge of such activities.

The Seismological Observatory of the University of Pittsburgh had its inception some 11 years ago in a gift to the University. It has been at various times a part of the Civil Engineering Department and of the Geology Department. Geophysical activities are now technically a part of the program of the Physics Department. Even though geophysical courses are listed with those of the Physics Department, the Observatory is separately maintained with respect to operating and library costs and research endowment. Work in meteorology was started two years ago by the Observatory and is separately maintained by it.

Other components of the earth sciences represented in the University are: geological engineering, mining engineering, and petroleum engineering, all in the School of Engineering; geology as a department in the college; and paleobotany as given by the Biology Department of the College. Thus it is easily seen that the major problem confronting the writer was one of interdepartmental cooperation and unification of efforts.

Summary of Factors to Be Considered

Before considering the details of the geophysical curriculum at the University of Pittsburgh, it would be well to summarize in brief what has been said in foregoing sections of this paper.

1. No artificial division should be made as to necessary background between applied geophysics and geophysics as defined by the American Geophysical Union.
2. Mathematics, physics, geology, and chemistry form together, and in their proper proportionate amounts, an indispensable background for the geological engineer, the modern geologist, and the geophysicist alike.
3. The specialist in any one of the parent sciences may only assist in geophysics; he cannot be called a geophysicist.
4. In the future the typical subordinate in industrial as well as academic geophysics will be the four-year graduate—but even his background should coincide closely with that of the more advanced superior.
5. Interdepartmental cooperation in the planning of course material and of curricula is a necessity.
6. There is as much true culture in science properly taught as there is in the humanities.
7. The student geophysicist must be examined both in his relation to society and as an individual.
8. The "trade-school" approach to geophysics will not fulfill professional requirements.
9. It is impossible to include all the necessary background material of the parent sciences and of the "tool" subjects in a normal four-year curriculum. This is especially true if there are additional and traditional cultural requirements.

10. We are not fair to the young geophysical student if we assume that he knows at the age of 18 what he wants in life. Any properly designed curriculum should include at least two trial years in geophysical background, from which, if the student wishes, he may transfer without loss of time or credit.

Curriculum of the University of Pittsburgh*

It was with these thoughts that the writer began the consideration of a geophysical curriculum. At the same time, but independently of the writer, Prof. R. E. Sherrill, Head of the Oil and Gas Department of the School of Engineering, started work on the reorganization of his curriculum in petroleum geology, which was to be changed to geological engineering. After several conversations it was found that some of the objectives of the two proposed curricula were identical. Many oil and gas students are at least casually interested in geophysical principles. Geological engineers should have at least a working knowledge of the geophysical solutions to their problems. On the other hand, geophysics majors should be acquainted with engineering methods and techniques, especially those which apply to natural resources.

Dr. Sherrill and the writer then collaborated in the design of curricula that would be as elastic as possible and would fulfill the requirements of the respective professional fields. So that students who are uncertain of their future vocation may shift from one field to another in the middle of their academic career, the first two years of the two curricula are almost identical. In fact, these two years represent standard engineering training. The student may register in either the College or the School of Engineering for these two years. At the end of that time, if he desires, he may change his registration without loss of time or credit. If he continues in the College, or changes registration to the College, he must then fulfill cultural as well as professional requirements.

* See next page.

The College of the University of Pittsburgh divides the various subjects under its jurisdiction into three general fields; that is, (A) The Humanities, (B) The Social Sciences, and (C) The Natural, Physical, and Formal Sciences. Included in each field are the subjects shown in the accompanying table. An undergraduate major in any one

Subjects in The College, University of Pittsburgh

Field A	Field B	Field C
Classics Fine Arts English Journalism Modern Foreign Languages Music Appreciation Philosophy other than Logic Speech	Economics History Geography History of Religion Political Science Sociology	Astronomy Chemistry Biology Geology Logic Mathematics Physics Psychology

of these fields must earn at least 12 credits in each of the other two, with certain restrictions. In the geophysics curriculum these field requirements are completed in the junior and senior years, in addition to upper-division work in physics, mathematics, geology, and geophysics.

Specific courses in geophysics as such are few. In the junior year, after the student has taken basic geology, physics, chemistry, and mathematics, he enrolls in Elements of Seismology. In this course are taught the theories of origin of the solar system; theories of crustal origin; the nature of, and relationship between, diastrophism, volcanism, and seismic activity, elastic rebound and the nature of the forces of deformation; elements of elasticity and elastic wave motion; laws of wave propagation and the use of time-distance graphs; travel-time charts for the various types of earthquakes and their use; instrumental means of detection, amplification, and recording; the various uses of seismological methods in exploration and in engineering. In the

Geophysical Curriculum, University of Pittsburgh

Freshman Year

First Semestre Course	Credits	Second Semester Course	Credits
English (1) Composition	3	English (2) Composition	3
Mathematics (21)	4	Mathematics (22)	4
Chemistry (3) General	4	Chemistry (4) General	4
Civil Engineering (1) Graphics	2	Civil Engineering (2) Graphics	2
General Engineering (1) Orientation	1	Industrial Engineering (2) Survey of Industry	1
Military Science (1)	1	Military Science (2)	1

Sophomore Year

Geology (1) General	4	Geology (2) General	4
Mathematics (23) Calculus	4	Mathematics (24) Calculus)	4
Physics (5) Engineering	5	Physics (6) Engineering	5
Economics (5) Principles	3	Civil Engineering (24) Mechanics	4
Military Science (3)	1	Military Science (4)	1

Summer Session

The Summer Course at Camp Hamilton, including surveying and geological field methods, is strongly recommended. At the discretion of the advisor, eight months of suitable industrial experience may be substituted for the field work.

Junior Year

Mathematics (100) Differential Equations	3	Physics (142) Heat	3
Physics (131) Light	3	Physics (64) Meteorology	2
Physics (163) Seismology	2	Geology (6) Structure	2
English (21) Literature	3	English (22) Literature	3
Elective (Field A)	3	Elective (Field A)	3
Elective (Field B)	3	Elective (Field B)	3

Senior Year

Physics (53) Electrical Measurements	2	Physics (54) Electrical Measurements	2
Geology (11) Economic	2	Geology (12) Economic	2
Geology (31) Mineralogy	2	Geology (32) Mineralogy	2
Geology (121) Petroleum	3	Geology (102) Advanced Structural	2
Elective (Field A)	3	Geology (104) Stratigraphy	3
Elective (Field B)	3	Physics (118) Geophysical Methods	2
		Elective (Field A)	3

second half of the junior year the student takes a course in meteorology, in which the meteorological elements and air-mass analysis and behavior are considered.

In the senior year the course in Survey of Geophysical Methods is taken. This course is taught by Dr. L. L. Nettleton, of the Gulf Research and Development Co. In addition, a worthy student undertakes an undergraduate thesis on an original problem commensurate with his ability.

During one summer, preferably between the sophomore and junior years, the student is strongly advised to attend Camp Hamilton, where he is taught geological field methods and surveying. This course cannot be officially required because of the overload of academic credits (the field course carries 11 credits) the student would have to bear.

During all of this time close contact is maintained between the student and the

geophysical faculty. The writer feels that more benefit may be derived by this contact in the discussion of problems than by additional formal courses.

With the four-year background outlined in the curriculum the student will be ready for more specialized courses in his graduate program. But he has not yet completed studies in all the "tool" subjects previously outlined. A graduate year is suggested in which some of these subjects are included. By the time the student has advanced to the graduate stage, it is assumed that he has a clear idea of his natural abilities and preferences, and that he will choose course material appropriate to those ideas. The writer agrees with Landsberg[3] wholeheartedly in this respect.

The curriculum at the University of Pittsburgh is not considered to be a finished product. Inevitably it represents certain compromises between cultural college requirements and necessary professional background. It represents a compromise between professional requirements and the inability of the student to know exactly what he wishes to do in later life. Lastly, the writer feels that the present curriculum represents the optimum possible when all the individual, economic, and traditional academic factors are weighed and fully considered.

We are attempting to inculcate in human beings the ability to think originally, and to help them to gain sufficient background and self-reliance to protect them in competition.

For those who are intending to pursue a course in geophysics that will allow more than mere routine in industry or observation, at least one graduate year is strongly recommended. Courses suggested for the graduate year are as follows:

	Credits
Physics (152) Electricity and Magnetism	4
Physics (107) Experimental Methods	3
Physics—Theory of Elasticity	3
Physics—Advanced Seismology	3
Mathematics (103) Advanced Calculus	3
Mathematics (104) Advanced Calculus	3
Civil Engineering (25) Strength of Materials	5
Civil Engineering (63) Hydraulics	2
Mathematics (217) Fourier Series	3
Physics (106) Treatment of Experimental Data	3
Geology (122) Sub-surface Methods	2
Geology (133) Microscopical Petrography	3
Geology (134) Microscopical Petrography	3
Geophysical Seminar (Required each Semester)	1

Thesis work to be done in one of the four leading branches of geophysics: seismology, meteorology, gravity, or electrical methods.

[3] H. Landsberg: A Geophysics Option in a Comprehensive Earth-science Curriculum. This volume, page 360.

The Professional Training of Geophysicists

Report of Geophysics Education Committee of Mineral Industry Education Division, A.I.M.E.*

(New York Meeting, February 1943)

The Geophysics Education Committee has devoted several years to a consideration of the problem of training geophysicists. Past reports have dealt largely with fact finding and with the discussion of particular aspects of geophysical education. In the present report it is proposed to review the subject more comprehensively. This involves the question of what educational qualifications the geophysicist of the highest professional standards should possess, and the related question of what changes must be effected in existing educational institutions in order that prospective professional geophysicists may obtain instruction of the desired quality.

The type of geophysicist here contemplated is one familiar with what is known already in the several branches of earth physics, and capable not only of following contemporary progress in any of these branches, but of contributing to that progress in a research capacity.

Geophysics in its broadest sense, as has been emphasized repeatedly by this Committee, is the study of the physics of the earth and of terrestrial processes. This includes both the static and the dynamic characteristics of the gaseous, the liquid, and the solid portions of the earth, as well as its gravitational, thermal, and magnetic and electrical manifestations. Some branches of earth physics have been cultivated but slightly; others have reached an advanced state of development. Those branches whose development is sufficient to warrant explicit recognition in the form of organized Sections of the American Geophysical Union are: geodesy, seismology, tectonophysics, and volcanology, dealing with the rock constituents of the earth; oceanography and hydrology with the aqueous constituents; meteorology with the atmospheric constituents; and terrestrial electricity and magnetism with the electromagnetic manifestations.

At present, instruction on the professional level in any of these branches of earth physics can be obtained in but few universities in North America. In most institutions where such instruction is undertaken different subjects are given in different and independent departments. Geodesy and hydrology are taught, if at all, as a part of civil engineering. The nearest approach to volcanology and tectonophysics ordinarily is represented by petrology and structural geology given

The Committee

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* Issued as T.P. 1633 in September 1943.

by the department of geology, and in but few instances has such instruction progressed to what might be called an advanced level. Seismology is taught most commonly in connection with the maintenance of a seismological observatory and frequently forms the nucleus of what is known locally as "geophysics." Modern dynamical meteorology and oceanography are closely related and are commonly taught together in an independent department. As recently as 1942, however, in only five institutions in the United States was advanced instruction in these two important subjects obtainable.

Within recent years a few institutions have taken steps toward giving instruction explicitly in "geophysics." In most instances these have assumed the form of survey courses devoted to the techniques of geophysical prospecting, offered as an attachment to the geology, the physics, or the engineering curriculum. In a few institutions separate departments of geophysics have been established, but advance instruction in most of these has been confined principally to one or two branches of earth physics, such as meteorology and oceanography, or seismology, or prospecting techniques.

There is as yet no school in North America with an advanced geophysical curriculum embracing the eight geophysical branches recognized by the American Geophysical Union, or their equivalents.

As a result of this state of affairs, few of those currently engaged in geophysical pursuits have had adequate or properly balanced training. Most have been recruited from fields for which training already exists—physics, chemistry, mathematics, engineering, or geology—and, in response to questionnaires from this Committee, they have complained of their educational deficiencies.

With this in view, the principal objective of the present report will be to inquire into the conditions that must be satisfied if adequate professional training is to be provided.

Educational Requirements

That the conditions to be met are by no means arbitrary can be seen at once by reviewing two aspects of the problem: (1) the present state of advancement of the separate branches of the field, and (2) the intrinsic nature of geophysical phenomena. To make such a review in a cursory manner it is convenient to divide the material constituents of the earth into two broad classes: the solids, comprising principally the rocks of the earth; and the fluids, embracing the surface waters of the earth and the gases of the atmosphere. To these material domains must be added the related gravitational, thermal and electromagnetic fields existing within and around the earth. Furthermore, not only are the geometrical relations existing among these several quantities at a particular time subject to inquiry but account must also be taken of the dynamic aspects involved in their changes as a function of time.

Since the solid portion of the earth, the so-called "lithosphere," comprises over 99 per cent of the total earth mass, a proper knowledge of it constitutes the very foundation of earth physics. In the first place the earth exists as a member of the solar system and is in a state of continuous motion with respect to the sun, moon, planets, and fixed stars. It rotates and precesses upon its axis, and revolves in an elliptical orbit about the sun.

An intimate technical knowledge of these astronomical phenomena is essential to the student of earth physics and requires, besides a course in descriptive astronomy, the following preparation in mathematics: plane and spherical trigonometry, algebra, analytical geometry, differential and integral calculus, and ordinary differential equations. In addition, physical preparation in elementary and analytical mechanics is required.

Next comes the problem of the shape of the earth and the distribution of matter near its surface and within its interior, as well as related tidal phenomena. One aspect of this problem is gravitational in character; another is seismological. On the gravitational side an advanced knowledge of the analytical properties of the gravitational field—the theory of the Newtonian potential function—is essential. In addition, the tides represent mechanical oscillators vibrating in response to periodically varying gravitational forces, introducing the necessity for a knowledge of the theory of vibrations.

The seismic aspect of the problem of the interior of the earth arises from the circumstance that the earth transmits by elastic-wave motion vibrations caused by sudden large disturbances. This requires an advanced knowledge of the transmission of elastic waves under a wide range of diverse circumstances.

On the experimental side the problem of the shape and mass distribution of the earth requires a variety of physical measurements of the highest precision: the measurement of geodetic base lines, astronomical observations, measurements of time, geodetic triangulation, tidal observations, precise leveling, and gravity measurements by pendulum, gravity meter and torsion balance. In addition, measurements in seismology involve the detection, accurate recording and precise timing of elastic vibrations ranging in strength from imperceptibility to the destructiveness of earthquakes, and in frequency from one cycle in tens of seconds to several hundred cycles per second, in addition to long-period earth tilts due to tidal and other causes. The types of apparatus required for these various purposes represent a wide range of mechanical, optical, electronic and electromagnetic equipment.

Hence, for this aspect of the solid earth, the student will need, in addition to the physics already specified, geometrical optics, electricity and magnetism, alternating-current theory applied to both electrical and mechanical systems, electronics, and the theory of physical measurements including the theory of probability and of least-square adjustments. In mathematics and mathematical physics he will require: functions of a complex variable, vector analysis and its application to the Newtonian potential function and to elasticity. A knowledge of the functions of a complex variable is necessary as the mathematical basis for both alternating-current theory and conformal mapping, the latter being essential in two-dimensional problems of physical fields.

In addition to problems pertaining to the earth regarded as a whole, there is field mapping, wherein, by means of detailed observations, a composite picture of the geometry of a particular area of the earth is obtained. This includes not only the mapping of the nonmaterial physical fields such as the gravitational, the thermal, and the electromagnetic fields of a given area, but the material fields—the geometrical configuration of the rocks and minerals—as well. Work of this kind presupposes the ability to make and interpret physical measurements, and to employ the theory and techniques of geology. The geological knowledge required includes the theory of geological processes, a knowledge of rocks and minerals, the regional distribution and relationships among geological formations and the history of the earth as deduced therefrom, and finally, the ability to do competent geological mapping, including the related techniques of drafting and surveying. The study of minerals and rocks presupposes a knowledge of inorganic chemistry.

To the foregoing phenomena, which are largely static in character, must be added the more truly dynamic aspects of the earth represented by the circulations and transformations of the material constituents of the atmosphere, the hydrosphere, and

the lithosphere, and the transformation of an energy supply derived from the radiation of the sun, the potential and kinetic energy of the solar system, and the intrinsic internal energy of the earth itself.

The simplest of these material circulations are those of the surficial fluids of the earth, the atmosphere and the hydrosphere, whose studies are already well advanced in the modern developments of meteorology, oceanography, and hydrology. For any of these closely related fields the student will require an advanced knowledge of the mechanics of fluids, the kinetic theory of gases, the theory of heat, and thermodynamics, in addition to more elementary subjects. The mathematics required is the same as that already specified, particularly vector and tensor analysis.

The slow diastrophic changes of the solid earth, sudden ruptures causing earthquakes, and intense folding in mountain-making are all manifestations of the behavior of stressed solids in a gravitational field, and represent the most general kind of problem in the mechanics of deformable bodies. This involves the analytical properties of fields of stress and the elastic, plastic, and viscous behavior of matter in the presence of stress.

The heterogeneous system comprising the rocks and minerals of the earth represents the most complex array of physical-chemical phenomena with which man has to deal. Rocks are composed of minerals, and minerals originate and disappear by physical-chemical processes. There are involved not only chemical changes evoked by the environmental factors, concentration, temperature, and hydrostatic pressure, already familiar to the physical chemist, but changes occurring in response to nonhydrostatic stress, a domain whose investigation is as yet hardly begun.

An essential tool in the study of rocks and minerals is the petrographic microscope, which, although capable of empirical use, can be comprehended only in the light of physical optics. The same knowledge, when combined with the theory of elasticity, affords the basis for the study of photoelastic models.

Next may be considered the earth's thermal field. Related to this is the disintegration of radioactive substances, serving at once as a major source of heat and as the best quantitative measure of geologic time. These require a knowledge of heat and of thermodynamics for the former, and of radioactivity for the latter. The earth's electromagnetic field and the reaction of earth materials to imposed fields must also be considered, and require, in addition to the experimental techniques of electricity and magnetism—particularly electronic apparatus—a knowledge of fundamental electromagnetic theory.

Finally, an integration of all of these apparently diverse phenomena may be effected when it is recognized that the thermal conduction, chemical changes, mechanical adjustments, fluid circulations, and electromagnetic phenomena of the earth are but details of a single vast thermodynamic system undergoing unidirectional and irreversible changes, an understanding of which is of fundamental importance and requires on the part of the student a knowledge of thermodynamics in its broadest sense.

The Geophysics Curriculum

From the foregoing it should be clear that the scope of earth physics is broad and that the problem that must be dealt with are by no means elementary in character. On the contrary, they encompass not only most of the data of geology, but involve almost the ultimate in many of the branches of classical physics and physical chemistry. The problem is how to assemble material of this sort into a single coordinated curriculum so that the student, after the usual seven years allotted to a

professional training, may go forth with the qualifications earlier stipulated.

A great deal of the training required for a professional earth physicist consists of instruction already available in the departments of physics, astronomy, mathematics, chemistry and geology of most universities and some schools of engineering. The essential element that is lacking, however, is the integration and unification of such studies into a science dealing with the problems of the earth. The possession of the knowledge specified in each of these separate fields no more constitutes a training in earth physics than a pile of bricks, cement, lumber, pipe and other building materials constitutes a house. This integration is the function of the instructional staff in geophysics.

The outlines of a curriculum in geophysics are presented in Table 1. Here the approximate scope of study in each of several required subjects is indicated. Practically the whole field of classical physics is specified with radioactivity and electronics in addition. The amount of mathematics demanded is that which is necessary for graduate work in the various branches of classical physics. In the table, courses in what might be called pure mathematics consist of the elementary courses in college methematics, differential and integral calculus, differential equations, and functions of a complex variable. Other courses, such as vector and tensor analysis, theory of probability, the theory of the potential, and other aspects of mathematical physics, which are sometimes classified as mathematics, are here assigned to physics. Chemistry, including a year each of general chemistry and of analytical chemistry, followed by at least one course in physical chemistry, has been specified. At least one course in general astronomy is needed.

In geology, a moderately complete review of all aspects of the subject on an undergraduate level is desirable. This includes general introductory geology, field geology, crystallography and mineralogy, stratigraphy and paleontology, and petrography. These will provide a good review of the present state of geological science and some familiarity with its methods.

A number of subjects have been classified as engineering. These are the tool subjects of shop practice, drafting, descriptive geometry and surveying. In institutions that do not have engineering schools, other provision for teaching such subjects either will be available or will need to be provided. Where not otherwise offered, drafting and descriptive geometry can be made a part of surveying. Shop practice is sometimes taught informally in connection with the operation of laboratory shops.

Besides these purely technical subjects, a number of courses giving as broad a background as time will allow in social phenomena, languages, biology and geography are suggested as an essential part of the undergraduate curriculum. A reading knowledge of scientific German is considered indispensable, and of other languages desirable.

It will be seen from the table that during his undergraduate years the student will be taking a broad miscellany of subjects in different departments. It is important at this early stage that the process of unification into earth physics be begun. This is accomplished by an elementary course in general geophysics offered in the second year. This course presupposes one year of college mathematics, a year of general chemistry, and is at least simultaneous with beginning work in geology and physics. It is brief and predominantly descriptive, serving chiefly to give a bird's-eye view of the field. In the fourth undergraduate year, it will be possible to offer a full-year course in geophysics on an intermediate level. At this time, the student will have had about two years of physics, three years of chemistry, mathematics through differential equations, introductory astronomy, and

TABLE 1.—*Proposed Curriculum for the Training of Professional Geophysicists*

	Mathematics	Physics	Chemistry	Geophysics	Geology	Engineering	Miscellaneous
GRADUATE, YEARS	Complex Variable	Electromagnetic Theory Radioactivity Optics Electronics A. C. Theory Thermodynamics Solid and Fluid Mechanics Potential Theory Probability and Measurements Vector and Tensor Analysis		EARTH THERMODYNAMICS TERRESTRIAL ELECTRICITY AND MAGNETISM CHEMISTRY OF EARTH PHYSICS OF FLUID EARTH PHYSICS OF SOLID EARTH			
THIRD AND FOURTH YEARS	Differential Equations	Electricity and Magnetism Heat and Kinetic Theory Analytical Mechanics	Physical Chemistry	INTERMEDIATE GEOPHYSICS	Petrography Stratigraphy and Paleontology Crystallography and Mineralogy		Social Studies Elective Language Scientific German Biological Science Humanities
SUMMER					Field Course		
FIRST AND SECOND YEARS	Calculus Analytical Geometry College Algebra* Plane* and Spherical Trigonometry	General Physics	Analytical Chemistry General Chemistry	ELEMENTARY GEOPHYSICS	General Geology	Surveying Descriptive Geometry Drafting* Shop Work*	Geography* English Composition

* It is desirable that these subjects be taken in high school.

most of his undergraduate geology. He is then in a position to review the separate fields of geophysics on about the level of an intermediate course in physics.

With this background, the student is ready for serious graduate work. He will require first more advanced courses in mathematics, and a general review of the various fields of classical physics in the light of a more unified approach made possible by the modern analytical methods employed in mathematical physics. Not until this time will he be able to do advanced graduate work in the various branches of the physics of the earth; and it is at this stage that the really important instruction in geophysics must take place. This is indicated in Table 1 by a full-year course in the physics of the fluid earth, embracing the fields of meteorology, oceanography and hydrology. Another full-year course is indicated for the physics of the solid earth, dealing with problems of the earth's motion, its gravitational field, its deformation, earthquakes and seismology, and with various of its other physical aspects. A third full-year course will be required for the chemistry of the earth, dealing with the physical chemistry of the changes that take place in the process of weathering, metamorphism, igneous phenomena, deposition of ores and the like. Terrestrial electricity and magnetism, although of itself a large subject, is related to the other aspects of earth physics in a manner that is not yet entirely clear. This subject is accordingly set aside as a separate study, the essential elements of which can be reviewed in a somewhat briefer course. Finally, as a means of unifying all of the phenomena previously dealt with, there is offered as a sort of "grand finale" a two-quarter or two-semester course in the thermodynamics of the earth. This course would review the factual material previously assembled by the more specialized courses, subjecting it to the powerful methods of analysis made possible by the first and second laws of thermodynamics.

In presenting the curriculum of Table 1 it is not intended that it shall necessarily be followed in minute detail or even that in the same institution every student take the same courses. Adjustments will have to be made to satisfy the requirements of separate institutions, and there is no doubt that the special interests of students in particular aspects of geophysics will permit them to omit certain of the background courses specified and to substitute others more appropriate to their individual needs. The main object of the table is to present in tangible form the approximate scope that must be covered in the several related subjects and the manner in which these may be integrated into a comprehensive training in geophysics.

No mention has been made of research. In a field as large and as undeveloped as the physics of the earth, this does not appear to present any problem. All branches of geophysics are replete with problems that constitute a standing challenge to the best research intellects we shall be able to produce for some time to come.

The Geophysics Staff

Having disposed in a general way of the curriculum requirements for the training of professional geophysicists, we have the remaining problems of the qualifications of a faculty and of the auspices under which such work can best be given. It is axiomatic with regard to academic instruction that with a given staff it matters little how much the curriculum may be changed or what the courses may be called; the actual instruction remains substantially unaltered. Consequently the mere setting up of a curriculum does not necessarily solve the problem of providing the professional training outlined. In the last analysis everything depends upon the choice of the instructional staff, the facilities provided, and the

freedom with which it is permitted to pursue the work laid out.

From the very nature of the program it is absolutely essential that every member of the instructional staff possess an advanced knowledge of the branches of physics and chemistry that bear upon the aspects of the earth with which he is to deal. In addition, all must possess a knowledge of the earth phenomena involved. It should not, however, be understood that what is proposed is a staff consisting simply of a miscellany of physicists and chemists. What actually is contemplated is a staff whose outlook is fundamentally geocentric in character—that is to say, whose problems are the problems of the earth—but whose analytical tools are the best that physical and chemical science can provide.

At this point the question arises as to the number of men required for such a staff. When it is considered that in institutions giving advanced instruction in meteorology alone the instructional and research staff consists of from three to eight members, it will have to be granted that if the remainder of earth physics is to be incorporated into the curriculum the staff should not be smaller. Since there is no well-defined upper limit to the size of a staff that might be engaged in active research into earth problems, let us try to indicate approximately the minimum that will be required for a satisfactory execution of this program. Such a staff might be approximately as shown in Table 2.

TABLE 2.—*Minimum Staff Suggested*

Subject	Number of Men
Senior Staff Members	
A. The Lithosphere	3
a. The earth as a whole	
b. Earth deformation	
c. Earth chemistry	
d. Earth thermodynamics	
B. The Atmosphere and the Hydrosphere.	2
a. Meteorology and oceanography	
b. Hydrology (including erosive phenomena)	
C. Terrestrial Electricity and Magnetism.	1
Junior Members	
Miscellaneous instruction and field work.	2 or more
Technicians	1 to 4

Anyone familiar with the magnitude of any of the subject groupings shown may justifiably question whether the number of men indicated is sufficient to handle adequately the subjects specified. In reply it can only be stated that the numbers given are intended to be minima and if the estimate be too low the obvious solution is to increase the number.

In the light of the foregoing discussion some of the problems with regard to geophysics that have plagued university administrators become irrelevant, or disappear entirely. When it was supposed that geophysics consisted solely of the application of certain much publicized prospecting techniques, it was generally assumed that the subject could be dealt with adequately by a single lecturer on a part-time basis, operating in one of the existing departments—geology, physics or engineering. When, however, the true magnitude and scope of earth physics is recognized and the magnitude of the task of training professional workers in the field is appreciated, such a procedure becomes manifestly impracticable.

This impracticability results from two circumstances. The first is that the operating unit in a university structure is the department. A department usually consists of a staff of from eight to twelve people, all of whom are working upon different aspects of a single unified subject. The second is that the students of a university, after a year or two of preliminary general work, become affiliated with a particular department and thereafter are subject to the administrative control of the officers of that department. They are directed to take most of the work that the department offers and only such outside work as its administrative officers see fit to require. The departmental requirements are designed to occupy all of the students' time.

In the present report it has been shown that the training of professional geophysirecists presents a unified goal that is dis-

tinct from the objectives of the existing departments. It has further been indicated that the magnitude of the task is such that it can only with difficulty be crowded into a seven-year curriculum. Consequently it is impossible to have the student fulfill the requirements of any of the existing departments and at the same time satisfy the conflicting requirements of a professional training in geophysics. Furthermore, as indicated earlier, the geophysics staff and its space and budget requirements are of the same order of magnitude as those of the existing departments. Hence any attempt to provide for the training of professional geophysicists by making such training an extension of one of the existing departments, without a complete overhaul of that department, is futile. The only administrative solution to the problem that appears to be at all practicable, therefore, is the establishment of the geophysics instruction in a separate and independent department.

Summary and Conclusion

During the several years of its existence, the Geophysics Education Committee has made extensive inquiry into every phase of geophysical education and has encouraged free discussion upon the different aspects of the problem. As a result of these discussions, it has become increasingly clear that although instruction in "geophysics" is offered in many universities, there is available in no institution in North America facilities for the well-rounded training of professional geophysicists. Some institutions give training on a professional level in certain geophysical subjects such as meteorology, hydrology, or seismology; others offer more abbreviated instruction, ranging from a few lectures to a few courses in the techniques of prospecting; others offer nothing at all.

Meanwhile, almost without benefit of academic sanction, the development of the various branches of earth physics is proceeding at an impressive rate. As a consequence, the demand for adequate training of professional geophysicists is becoming increasingly insistent. That positive action to meet this demand will soon have to be taken by institutions of learning is taken for granted. The concern of the present report, therefore, is not *whether* geophysical instruction will be given, but *what* instruction and under what auspices.

In its past deliberations, the Geophysics Education Committee has sponsored, both by its own members and by others, papers favoring the offering of such instruction in various of the existing departments. After mature consideration of the results of efforts along such lines, it is concluded that all fall far short of the desired goal. As far as can be seen at this time, there appears to be no really adequate solution to the problem of the training of professional geophysicists short of the establishment of independent departments with staffs, equipment, and budgets comparable to those of other departments. That such departments be established, having the scope and professional point of view herein indicated, is the recommendation of this Committee.

DISCUSSION

Too Complex a Program

C. H. Behre, Jr.,* New York, N. Y.—One may be in general sympathy with the objectives of the well written report prepared by the Geophysics Education Committee without agreeing with all the specific recommendations as expressed in the words of those who designed the report. I find myself in that position. The report is excellent in pointing out that progress in general geophysics, especially in the more theoretical and basic aspects of that field (in contrast with the technique of searching for minerals), demands a fairly distinctive basic curriculum. To set up such a curriculum requires three things, which are quite properly emphasized in the report: (1) recognition of the fact that geophysics, though clearly on the borderline of two and closely adjacent to three other sciences, is a field fairly distinct in its

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requirements from either physics or geology; (2) establishment of an adequate staff and equipment, especially if those are not already provided in the related departments of the college or university; and (3) placing the curriculum in the hands of those competent to advise and to examine the candidates.

The value, if any, of a separate comment (such as this aims to be) is in its constructive criticism and this will arise out of points of disagreement rather than of approval. To the writer these points are three:

1. Geophysics is made too broad a term, and thus contributes the same error as geology when that term is used to cover all of geophysics. It should not, for instance, be construed to include geochemistry, an adjacent field but one that differs strikingly, especially as to emphasis. Geochemistry deals with such matters as the chemical composition of magmas, the composition of mineralizing solutions, the changes involved in converting a petroleum of one base to that of another, and the nature of the lesser elements in organic compounds. None of these is primarily a geophysical problem. I suppose two reasons for this too broad construction are: (1) the fact that the greatest institution in the United States for investigating geochemical *and* geophysical problems happens to be called the Geo*physical* Laboratory, and (2) that there are far more practicing and theoretical geophysicists than geochemists. Even this last disproportion may change, however, if the work of McDermott and others in searching for oil by surface analysis proves highly fruitful.

2. It is an error to think that, in order to set up a feasible undergraduate or graduate curriculum, a separate staff, designated the Department of Geophysics, is required. What is needed is solely a skeleton organization which, however, has the power to design a geophysical curriculum that cuts across departmental lines to whatever extent is desirable. This suggestion is in accord with the policies of most universities and colleges today, for universities are now seeking to reduce the stultifying influence of some departments that feel a vested interest in a specific technical curriculum. There is much to be said for associating exploratory geophysics with mining; seismology and sedimentation with geology; meteorology with climatology and geography; and geodesy with civil engineering. In many institutions these associations are grounded in history, and in all but the very largest they are affected by the personal backgrounds and qualifications of the individual teachers. But even without establishing a Department of Geophysics (an action that might well touch off one of those wordy wars that shake colleges to their foundations!), those concerned with all types of geophysical curricula could easily form a committee to advise and examine the graduate candidate in this field.

3. It is an error to demand too much background. The plan outlined by the committee should be viewed as an ideal, especially as to prerequisites, but not as a *sine qua non*. For this there are at least two good reasons. The first is that the science of geophysics—if it is a separate science—is still very young. As such it will gain in value and grow in stature as it draws in scholars from other, overlapping fields. A recruit from graduate work in geology will be weak in respect to physics; with a recruit from physics, however, these weaknesses and strengths will be reversed.

More important, however, is the fact that college and university students largely discover their major interests only a considerable time after they have started their higher training. It is wiser to accept such people and gradually allow them to acquire the desirable background than to shut the door in their faces. As a matter of common experience, even mature investigators acquire much of their techniques relatively late and frequently only when the need for a particular attack becomes apparent. Of distinguished scholars in geology belonging to the writer's generation, for example, one was already far advanced in training as a chemist, a second as a zoologist, a third as a medical man, and a fourth as a psychologist, before in each case they swung into geology. Had these men been faced with the ideal basic curriculum for geology and told that their choice would lie between acquiring that background by four or five more years of study or giving up geology, four of our most able American geologists would have been lost to the science.

The fixed curriculum, which is the essence of the recommendation of the committee, is not well adapted to the American pattern, with its social and economic fluidity, its educational system shallow in background but varied in

possibilities, and its lack of insistence upon specific degrees or other formal requirements before the candidate may practice or do research in his chosen line. We may not like this flexibility and wealth of options (though I, for one, prefer them), but it would be a mistake to plan a curriculum without considering the qualities of the country in which it is to operate.

In brief, the committee should set its sights a little lower by: (1) eliminating from the *required* courses those subjects not basic to geophysics; (2) reducing the emphasis upon the increase of the geophysical staff and its separation into an autonomous department; and (3) requiring a background not so extensive as to divert talent into other fields where research can begin earlier.

With the general plans favored in the report, and especially with its idealism and its emphasis on the significant role of geophysics, I am in heartiest agreement.

Geophysical Education Ad Infinitum?

C. A. HEILAND,* Golden, Colo.—The sentiment indicated in the subtitle above—or possibly a stronger, equally familiar one—states in a few words the reaction of A.I.M.E. members who have expressed themselves to me about our protracted discussion of geophysics education. Some of them remind us, not without justifiable sarcasm, that a real geophysicist should be too busy with war work to bother with a topic which, for the duration, appears to be a dead issue.

It is true that at present the place of the geophysicist is in research, development and construction of military equipment, or in geophysical exploration for petroleum and other strategic minerals. To talk now about geophysical education may seem indeed somewhat out of place. However, I have been asked to submit my comments on the last report of the Geophysics Education Committee, and hope that I will be forgiven for going into some detail notwithstanding the objections referred to above, particularly since I have not partaken in the discussion for several years.

Fundamental Issues.—As so often happens in prolonged discussions, differences of opinion arise from the fact that the fundamental issues are not clearly defined. I am sure that many in the Committee have not realized that a subject of both commercial and scientific aspects cannot be taught by a single educational formula. *One type of curriculum is required for geophysical exploration, quite another for geophysical science.*

In its last report the Committee has gone all out for a geophysical science curriculum. In our discussions extending over a period of five years we have drifted farther and farther away from geophysical engineering, notwithstanding the ever increasing economic scope of that subject. In its 4500-word report, the Committee devotes barely two or three sentences to what are called "certain much publicized prospecting techniques." It so happens that by the end of 1942, geophysical prospecting had found, in the Mid-Continent and Gulf states alone, about seven billion dollars worth of oil. That was done by exploration geophysicists, and not by astronomers, meteorologists, hydrologists or volcanologists, whose training we are now expected to substitute for that of the exploration geophysicist.

To me, the latest recommendations of the Geophysics Education Committee are all the more surprising because this Committee represents an engineering organization. Moreover, the Committee is supposed to be a part of the Mineral Industry Education Division. If there is any reference in the Committee's report to the mineral industries, I have failed to find it. From the viewpoint of the mineral industry, the A.I.M.E. is principally interested in the exploratory phase of geophysics. The scientific aspects of geophysics dealing with the composition and dynamics of atmosphere, hydrosphere and lithosphere are quite ably handled by the American Geophysical Union. There is no need for overlap or duplication. The last Committee report reads as if the American Geophysical Union had sponsored it, not the A.I.M.E.

Engineering.—Previous Committee statistics show that geophysicists employed in geophysical exploration far exceed those engaged in geophysical science. It is but natural for these men to ask how it is possible for an engineering education committee of an engineering organization to recommend an advanced curriculum so foreign to geophysical engineering. The answer lies in the fact, I believe, that it is

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difficult for geophysical scientists to appreciate the principles of engineering and engineering education and to view them in their correct perspective.

To me, engineering means translation of scientific principles into practice, combined with design and management to do things better, cheaper and faster. Geophysical exploration or geophysical engineering is essentially the location of mineral deposits by geophysical measurements. It is good geophysical engineering to compensate magnetometer and gravimeter systems for temperature variations; to measure physical rock properties in situ rather than in the laboratory; to replace analytical methods of calculating corrections and subsurface effects by curves and nomograms; to institute labor-saving and time-saving devices in the field; to select personnel on the basis of technical qualifications as well as ability to get along with others; and finally, to submit reports showing an intelligent consideration of geologic possibilities. It is poor engineering to design instruments in such manner that they will not stay in adjustment in the field or cannot be taken apart without undue difficulty; to calculate corrections with an accuracy exceeding that of the field observations; to submit a map with crossed contours; or to interpret a geophysical indication as being a salt dome in a granite basement. Those who think that these examples are ridiculous or extreme are referred to the earlier literature in which advocates of nonengineering approaches to geophysical exploration have openly sanctioned such things under the guise of scientific license.

Engineering Education.—In the Committee's discussions that I have had an opportunity to attend or to read, engineering education appears to have been confused with shop training, or with the training in special techniques. The often-heard argument: "We do not want a prospective employee to have to unlearn what he has learned in college" is absurd on its face.

1. Real engineering education deals with fundamentals, and uses instruction in techniques merely as illustration of the same.

2. Geophysical techniques demonstrated in geophysical engineering courses differ no more from average commercial practice than they do between individual companies. If this argument of "unlearning" techniques were true, why did some geophysical and oil companies, in peace time, hire operators, computers, party chiefs, and research workers away from each other?

3. In other fields of engineering, commercial companies hire engineers, not scientists, for their engineering jobs and often for their research jobs. In this manner unnecessary duplication in company instruction of engineering fundamentals is obviated, and it is only necessary to instruct the men in specific company practices. To encourage such engineering training in college and to keep it up to date, companies are in the habit of contributing by loans and donations of equipment. I have heard it said that employers prefer to train their geophysical engineers from the ground up. I know that such companies are now in the minority. Even 4 or 5 years ago, this was indicated by the Committee's own findings, on which we read the following comments, in the 1940 report, under the heading of Opinions of Employers: "Lack of field practice came third . . . , followed closely by the need for better instruction about geophysical instruments. . . . It is interesting to see how a large number complain that their employees are deficient in training with geophysical instruments and in field practice. . . . A good many correspondents expressed the belief that students should be taught use of instruments in the field." My opinion is that operators in the geophysical service business and in oil exploration are not such poor educators or businessmen as not to take advantage of a well-rounded fundamental college training in geophysical exploration.

4. In the course of the past 17 years, a number of men have been sent to our institution by foreign governments, to study geophysical exploration, not geophysical science. Further, we have had men desiring to be independent consultant geophysicists, and men intending to take charge of geophysical exploration departments for oil and mining companies. How would these men learn geophysical exploration if an educational institution were to confine its instruction only to geophysical science as now suggested in the Committee's report?

5. Not only is it impossible to hold the attention of an engineering student by a purely theoretical discourse, but it is poor practice *not* to use examples of operation and interpretation as illustration of the theory. To

condemn such practice is like criticising laboratory work given in conjunction with qualitative chemical analysis. As it is, we at the Colorado School of Mines are often criticized as being too theoretical. On the other hand, we also hear that our equipment in some instances is better than that our graduates have to work with later.

Some rather deprecating remarks were directed in our meetings against engineering schools and engineering education five years ago. I questioned their validity then and do so now. Besides, the situation has changed since then. We now find that the last Committee report, far from keeping pace with the times, omits from its recommendations any and all courses in magnetic, gravitational, seismic and electrical exploration. Just think of training an electrical engineer only in theoretical physics—without instruction in the design of electrical equipment! Or of turning a medical student loose on an operation after teaching him only the elements of anatomy!

To repeat: From the viewpoint of the mineral industries, the function of the exploration geophysicist is to locate mineral deposits. The mineral industries are not particularly interested whether he knows astronomy, meteorology, or oceanography. If a mine operator or oil man hires a geophysical engineer he is paying him, directly or indirectly, to find an ore body or an oil pool. He is not paying for a discourse—and I quote from the report—on "the geometrical relations existing among . . . the gravitational, thermal and electromagnetic fields . . . at a particular time . . . and the dynamic aspects involved in their changes as a function of time."

Perspective.—To appreciate the need for engineering education in geophysical exploration, it is necessary to view this subject in its correct perspective and in relation to other branches of engineering. In the early stages of other engineering subjects, education in general science or specific sciences was sufficient. In the days of limited uses of electricity, training in physics and in electricity provided sufficient background to handle industrial assignments. With the tremendous upswing in industrial uses of electricity with all of its ramifications, this is no longer true. We now have not merely one, but many different types of electrical engineers—the power engineer, the electrochemical engineer, the illumination engineer, the communications engineer, the radio engineer, and the electronics engineer, to mention only a few. An individual with science training in physics or electricity alone would be hopelessly unprepared to cope with the competition.

Another example, more directly pertaining to the petroleum industry, is that of the petroleum engineer. There was a time when training in geology and mechanical engineering was sufficient for the production engineer; and training in organic chemistry, physical chemistry and thermodynamics sufficed for the refiner. As far as geophysical exploration is concerned, there was perhaps a time when a man with geophysical science training had sufficient background; he learned the rest on the job. However, that time is gone. To appreciate this and to consider geophysical engineering in its correct perspective—past, present and future—requires, of course, a substantial background of practical experience in all geophysical methods and not merely a passing acquaintance with the subject. I believe that I can qualify to speak of perspective, having devoted 22 years to geophysical exploration practice, of which ten years have partly been given over to helping a commercial company over its growing pains. I dare say that there is hardly a better place to get a perspective of geophysical exploration.

Fundamentals in Curricula.—Lest I be misunderstood I want to be emphatic about one point. Training in a subject of both industrial and scientific aspects must of necessity include the *same fundamentals* in the engineering curriculum and in the science curriculum. In other words, a geophysical exploration curriculum must include mathematics, physics, chemistry and geology in the undergraduate section, and the same is true for geophysical science training. From then on the geophysical engineering curriculum should concern itself with lectures, laboratories, and field work in geophysical exploration methods, while the geophysical science curriculum may go on with instruction in such subjects as terrestrial magnetism, seismology, oceanography, hydrology, etc. It is for this reason that I agree with the Committee's recommendations for undergraduate study in the fundamentals, but disagree with their graduate science course and believe it to

be unsuited for the requirements of geophysical exploration.

Length of Course.—A total of at least seven years of undergraduate and graduate study is recommended in the last report of the Geophysics Education Committee. Such a suggestion simply fails to take into account the practical realities. To begin with, any successful education program has to reckon with three factors: the student, the college administration, and the professor (or a reasonable facsimile thereof). What student is going to sit through seven years of (probably very dry) science lectures in a subject that he knows to have intense practical applications? Would it be possible to keep him from getting his hands on a magnetometer, a gravimeter, or seismograph if he knows that he will have to work with these instruments? How are we to keep him from going out into the field to see what an anticline, a salt dome, a magnetite dike or a sulphide ore look like in the seismic, gravitational, magnetic, or electrical picture? The answer is that a student will go to an institution where he can get that opportunity.

Furthermore, how are we going to keep a student in school for seven years when there are companies bidding for his services at the end of four or five years? Are we forgetting that there are practically no geophysics students now, and that at the end of the war there will be a terrific scramble for men? With an oil shortage staring us in the face in a few years right here in this country; with the world supply of most metallic minerals (with the possible exception of iron, aluminum and magnesium) running dangerously low as the result of the war, what right have we to waste manpower on a seven-year curriculum, with *one year* devoted to meteorology and oceanography, a *second* year to seismology, and a *third* year to geochemistry—courses that can be dispensed with in favor of others that give a man the tools with which to find the much needed raw materials?

Undoubtedly, it would be nice for an exploration geophysicist to know all these things. However, there are practical limitations to what he can take. When it comes to a choice, training in exploration geophyics is more important to him than instruction in geophysical science. It would also be nice for an economic geologist, since he uses paleontology now and then, to take courses in biology, botany and zoology (I've taken them myself). But to *require* them of a geologist, when there are so many other more important things to learn in the available time, is simply impracticable. By the way, have we forgotten that little incident when a number of students from an eastern university remonstrated in one of our meetings against being loaded with too many "unnecessary" subjects?

What administration do we expect to sanction a program that takes an altogether disproportionate number of professors (the report suggests a minimum of about 10) in comparison with the number of students that will want to take a science course? Relative to the professor's qualifications, I venture to say that a wide-awake student of geophysical exploration will want a teacher with practical experience who knows what he is talking about. Men with such background will be few and far between when there are better paying industrial positions to be had.

Finally, how many companies will want students with seven years of science training? Maybe there will be a niche for them in somebody's research department, but I doubt whether such men will have the common-sense approach so necessary in a practical subject. I dare say that it will be easier to make a good research worker of an engineering student with good fundamental training in mathematics, physics, geology and geophysical exploration, plus some well-rounded field experience, than of a seven-year student in geophysical science who may be approaching the crackpot stage.

Another thing we have to be mindful of is the effect of the war on educational programs. It is generally conceded that this is a war of physics, and it is quite likely that in the post-war period, education in physics and mathematics will be stressed more than heretofore. It is conceivable that a large portion of mathematics and physics, now taught in college, will be relegated to the last years of high school. This would leave the four college years open for advance science or engineering training; seven years would be quite unnecessary for a curriculum in either geophysical exploration or geophysical science.

A Workable Course.—In order not to be misunderstood, let me re-emphasize that *I have no objection to a geophysical science curriculum for a geophysical scientist.* I have tried myself to

introduce geophysical science courses into our curriculum. This worked fairly well as long as comparatively little was known about geophysical exploration. When geophysical exploration grew in scope, when methods became more or less standardized and stabilized, the courses in geophysical science fell by the wayside. The chances for geophysical science courses may possibly be better in a school where no geophysical exploration courses are offered; yet I hear that in one university where the introduction of a graduate curriculum similar to the one now proposed by the Committee was tried, the attempt was unsuccessful.

My own recommendation for a geophysical exploration curriculum can be put in very few words: fundamental undergraduate training in all engineering subjects, particularly *mathematics*, through differential equations; *physics*, both theoretical and experimental, particularly electricity, magnetism, communication and electronics; *chemistry*, including general chemistry, qualitative analysis, organic and physical chemistry; *geology*, inclusive of mineralogy, petrography, paleontology, sedimentology, stratigraphy, historical geology, structural geology, map interpretation, ore deposits and petroleum geology, preferably supplemented by at least one-half year in a mining area, or in an oil field. In the third or fourth undergraduate year there should be an orientation course in geophysical exploration for geologists, mining engineers and petroleum engineers. This would be followed in the graduate year by *advanced courses* in *magnetic*, *gravimetric*, *seismic*, and *electrical prospecting*, with a proper balance of lectures, laboratories and field surveys. This is a *workable course*. With the exception of the fact that we are now forced to offer this curriculum in four years, this is the course that has been offered in substantially this form for many years at the Colorado School of Mines. In view of this, the following statement made in the 1940 report of the Geophysics Education Committee is not understandable: "More than 50 universities . . . have sent graduates into geophysical careers, in most instances without specialized courses preparing them for such a profession. There is no single institution in this country offering a completely rounded introduction into a career in either exploration geophysics or in the broader field of the physics of the earth." If the Committee feels that a graduate *science* course is necessary for a completely rounded instruction in exploratory geophysics, I disagree. The fact remains that a total of 606 students have taken our geophysical courses to date, which represents about 30 per cent of the 2000 technically trained men now employed in geophysical exploration. A substantial number of former students are now in executive positions with leading geophysical companies.

By contrast, the graduate earth's-science curriculum proposed by the Geophysics Education Committee has, to my knowledge, not been adopted for exploration geophysicists by any educational institution in the United States.

Reply to Dr. Heiland's Discussion

S. F. Kelly,* Amawalk, N. Y.—Dr. Heiland's implication that discussion of geophysics education is now out of place, because the topic is a dead issue for the duration of the war, reflects, it seems to me, a shortsighted view of the vital role *all* education must play, not only now but in the post-war world. To defer consideration of the subject until the last bullet has been fired, and the hordes of returning soldiers swamp our industrial and educational institutions, could lead only to confusion, delay, and faulty improvisation. Wasted effort, wasted time and wasted manpower would multiply the problems of post-war adjustment. In our own field, delays of serious proportions would intervene in replenishing the supply of geophysicists which, Dr. Heiland rightly predicts, will be urgently needed in the program of rectifying the war-induced depletion of world mineral reserves.

When taking issue with so eminent an educator as Dr. Heiland, however, it is encouraging to see other, equally eminent educators also advocating an unrelenting study and continued reform of the educational system. Dean Gildersleeve, of Barnard College, returning in August 1943 from a tour abroad, reported that Britain, in the midst of war, is "buzzing with interest in education." In September of this same year the *New York Times* carried an article describing the White Paper submitted to the British Parliament by the Board of Educa-

* President, Sherwin F. Kelly Geophysical Services Inc., Wilmington, Del.; Geophysical Explorations Ltd., Toronto, Ont,, Canada.,

tion, which contained an outline for educational reconstruction in Britain. During that same summer, the American Federation of Teachers pledged its unequivocal support to the country's war effort, and its President, John M. Fewkes, declared that "Education will be the foundation stone sustaining any permanent peace. The teachers of the world will be the masons." Must our educators be reminded not to lay down their academic trowels?

With this moral support I venture to offer some comments on Dr. Heiland's criticism of the 1943 report of the Geophysics Education Committee. Although as a member of that Committee I signed the report, I agree with Dr. Heiland's criticism that it gives too short a shrift to the problems of educating for geophysical exploration. This is the phase that is of prime interest to the Institute, therefore it should have bulked larger in the report.

But his statement that "one type of curriculum is required for geophysical exploration, quite another for geophysical science" is, it seems to me, open at least to some question. The curricula will differ in the graduate years, but in the undergraduate courses the *type* will be the same—thorough grounding in fundamental theories, schooling in the practical applications of those theories, and training in the manipulation of the instruments through which field practice is achieved. The art of geophysical prospecting cannot be divorced from the geophysical sciences, for it stems, in modified form, from those same sciences; efficient magnetic prospecting cannot be carried out in ignorance of terrestrial magnetism, seismology is the parent of seismic prospecting, geodesy of the gravitational survey, etc.

The fundamental theories of these geophysical sciences therefore have their bearings on the work of the geophysical prospector. Dr. Heiland seems to recognize this by his admission that he tried to introduce geophysical science courses into his own curriculum, and was forced to drop them only under the pressure of an increasingly crowded schedule. In quoting from the 1940 report of the Committee concerning deficiencies in academic training, "Lack of field practice came third (37 per cent), followed closely by the need for better instruction about geophysical instruments," in support of his well-founded contention that practice in geophysical techniques is essential for the student, Dr. Heiland neglected to mention the preceding sentence in that report. On page 91* it is emphasized that those same employers who complained of poor practical training found that the *greatest* deficiency exhibited by their own geophysical staffs was in the field of geophysical theory (58 per cent)! Let this be our excuse for bringing under discussion those fields of geophysical science which, at first glance, may seem to be but remotely related to geophysical prospecting.

If further encouragement is needed for this seemingly heretical procedure, it will be well to recall the words of advice uttered at our meetings in 1940 and 1941 by Prof. Richard M. Field. As President of the American Geophysical Union, he called attention to the fact that sound advance in geophysical science required the engineering approach, and that no other engineering organization was sufficiently interested, or in as favorable a position, as the American Institute of Mining and Metallurgical Engineers to foster this necessary view of these earth sciences. It will do us no harm if we inspect our field of study through the telescope rather than the microscope.

Throughout its discussions the Committee has been acutely aware of the almost insuperable difficulties presented to any attempts at formulating an adequate geophysics course which can be encompassed in four academic years. In citing his own curriculum, Dr. Heiland recognizes the unsatisfactory character of such a course when he laments that "We are now forced to offer this curriculum in four years." This necessity may explain the earlier findings of the Committee that no single institution in this country offers a completely rounded introduction to a career in either exploration geophysics or the broader field of the physics of the earth (p. 89, vol. 138). Although I do not have access at the moment to the returned questionnaires upon which that statement was based, my recollection is that *not a single one* of the 122 practicing geophysicists who answered the questions, including graduates of the Colorado School of Mines, expressed complete satisfaction with the academic course he had followed. This situation must be recognized in offering recommendations for a thorough course in geophysics,

* *Trans.* A.I.M.E. (1940) 138.

and may well necessitate carrying academic preparation past the traditional four years.

An alternative solution was proposed in the 1942 report of this Committee, wherein the suggestion was made that certain courses, now given in college, could quite adequately be presented in high school, leaving the university years free for attention to more advanced work. This is a solution which Dr. Heiland now recognizes as a possible one for the dilemma facing us. A further suggestion made during the discussion of that report was that our concept of the academic year be revised, and by shortening the summer vacations, and rearranging the schedules, the same instructional material could be given in two to three years. It is very encouraging to observe that the necessities of war have compelled the adoption of just such a program, although the year before several educators present at that geophysics session stoutly maintained that such radical departure from tradition was impossible!

It seems to me that the establishment of a satisfactory geophysical curriculum can be achieved only through the correlation of efforts along several lines. Elementary subjects that can be given at high school level should be taken out of the college courses to make room for more advanced studies. If, after this is done, four years still prove inadequate for giving a well-rounded preparation in geophysics, we could abandon the traditional concept of the academic year, and introduce our students, at an earlier stage in their development, to working conditions that will more nearly simulate those they will encounter after graduation. The courses to be given should emphasize the fundamentals, in which Dr. Heiland is in agreement with the Committee reports of 1942 and 1943. The students envisaging careers in geophysical exploration should certainly be given a knowledge of the other fields of geophysical science, especially those theoretical phases having a bearing on what they are themselves to practice. The applications should unquestionably be illustrated by field work and instrument manipulation, but the emphasis should not be on the minutiae of these operations—they are but to illustrate principles.

The curriculum offered in the present report can easily be modified, by any institution, to meet the objections raised by Dr. Heiland. Provision is made for geophysics courses in the undergraduate years which could be devoted in part to instruction in geophysical prospecting for those students who plan to enter the profession without graduate training. In the graduate years, training in the geophysical sciences could be considerably reduced in favor of graduate work in geophysical exploration, theory and practice, for those men who plan a more advanced training in the art and science of geophysical prospecting.

In offering the curricula cited in the 1942 report, the Committee endeavored to make them as flexible as possible, so they could be modified to suit particular conditions; a similar flexibility should be envisaged for the curriculum now presented. This same flexibility was provided in the recommendations submitted in 1942 as to the department in which geophysics should be taught. The "Conclusion" of this 1943 report implies, however, that the previous Committee report recommended the inclusion of geophysics in the department of geology. Lest that implication be misunderstood, I should like to point out that the previous report specifically states,* "In view of these circumstances, the optimum place for geophysics in a university at the present time may well be as a separate institute or department. It could thus have its own staff and research facilities, with complete control over its curriculum . . . " The wisdom of reinforcing that recommendation in the present report is underlined by the continued unfavorable attitude of some geologists and educators who still fail to realize the role of geophysics in the study of the earth.

From a Former Chairman of the Mineral Industries Education Division

W. R. Chedsey,† Columbus, Ohio.—I agree with Dr. Heiland most heartily that a seven-year science curriculum in theoretical geophysics is not needed. I thoroughly agree with him that we should have at least a few well-balanced geophysics curricula with enough basic underlying science to be sound and with enough practical applications shown to be at least of a semiengineering character. His own curriculum is unquestionably one of the best.

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* Report of Geophysics Education Committee, 1942. Page 368, this volume.

† Consulting engineer.

Some five or six years ago, when the Geophysics Education Committee was formed separate from the Committee on Geophysics, we outlined a program investigating what was being done in the way of teaching geophysics and what various people thought could be done to "standardize" or improve this new and rapidly growing subject. We projected this study over a four-year period and I recall that Dr. Heiland attended some but not all of the sessions of the committee

In 1942 this particular phase of the work was wound up and such suggestions as the committee had were stated, but without being strong recommendations, thus leaving to the initiative of those concerned such application as they might care to make from the facts found by the committee.

At the same time I ended my term as chairman of the Mineral Industries Education Division, and owing to pressure of war work, have pretty well lost track of later developments, so that Dr. Heiland's discussion deals with something that I had not previously seen, unless by chance he was referring back to some phase of the earlier four-year study. As he does refer in one or two places to that earlier study and report, it perhaps needs a certain amount of explanation.

Near the top of page 409, he says, "Some rather deprecating remarks were directed in our meetings against engineering schools and engineering education. . . ." That was a period in which the Engineers' Council for Professional Development was making a study of engineering colleges and finding many grave faults. Perhaps it was only natural that some of these ideas should get into our meeting, particularly as everybody was making a further conscious effort to analyze his own curriculum and to make improvements upon it. Most of these improvements were the strengthening of the basic or underlying courses in mathematics, physics, chemistry and mechanics.

On page 411 he quotes from the 1940 report and then defends his own curriculum. At the beginning of that same paragraph, he outlines a suggested and probably ideal curriculum and then ends by saying, "With the exception of the fact that we are now *forced* to offer this curriculum in four years . . . " (the underscoring is mine), which immediately shows that even his is not a completely rounded curriculum. Again I subscribe to the fact that his is probably the best in the country, yet I think he shows that it is not at present his ideal, which was what the committee was driving at.

Both Mr. Kelly* and I felt that the later discussions in 1940–1941 were beginning to get a little unbalanced. We needed the attendance and the contributions of those who were interested in the underlying basic sciences and they turned out in large numbers. We also needed the attendance of the practical geophysicists, and they almost invariably "ran out on us," even those who undoubtedly were interested in the education features of our discussions. Dr. Heiland admits this on page 11. That was another reason for our bringing our projected study to a close, so do not blame the committee that is doing the work, at least those who were working at that time.

Some five or six years ago there were a number of proponents, and strong proponents, of their own pet geophysical methods, and many of the curricula naturally, in going through the literature, reflected this condition. Some of these seemed, if not actually in contradiction, at least to make some diverging but seriously overlapping claims. Those of us in teaching work felt that it was dangerous to build a course upon only such techniques, with an underlying basis of geology, and thus we wished to draw in the other underlying subjects, at least to investigate their bearing on the whole problem.

I think it will be agreed that some one or more features of all of those various theoretical sciences which Dr. Heiland mentions have some bearing on the interpretation of some of the practical techniques used in the field. With this phase of the subject again getting out of hand, it may be just the proverbial "swing of the pendulum," but in any event one of the reasons that it could get out of hand was the lack of interest of some of the practical group in our discussions. As I said before, we thought we had this phase of it not only adequately covered in our work ending in 1942, but we believed we also had any further emphasis on it "stymied" off, therefore I am surprised that it has not only crept back but apparently dominated a later report.

The American Geophysical Union cooperated with us and various members were very helpful

* Then Chairman of the Geophysics Education Committee.

in the discussion, but apparently did not in 1940 and 1941 ascribe undue importance to the theoretical phases which they mentioned.

I have not meant to be critical of any one even in his failure to attend all of our meetings, because I know that all are busy, but I do want to make clear some of the background. If Dr. Heiland had clearly understood it, he might have modified his discussion.

I believe that geophysics as it is taught generally could be improved, particularly in the strengthening of the basic sciences. If there is not time to teach all of the field techniques, a few typical ones could be chosen to show the application of the various principles involved.

Let us go ahead with further sound developments of the important subject: training of young men *thoroughly* in the necessary basic sciences and with enough field work to make them immediately valuable.

Twenty-five Years Experience

Hans Lundberg.*—After 25 years in geophysical exploration, it is interesting to look back on the results of one's efforts during that time. Some outstanding and very rich finds were made in the beginning, and naturally, these created a great deal of enthusiasm. The development of the methods for oil prospecting followed very different courses to those for ore prospecting. The returns in oil prospecting were so tremendous that expensive equipment and experiments could be afforded and, gradually, each oil company started its own department of geophysical exploration.

In ore prospecting, the returns naturally were more moderate and therefore less money was spent on apparatus and development of methods. But in spite of this, a number of very successful methods have resulted. Below, I am confining my remarks to development in prospecting for ore.

Geophysical prospecting for ore requires special knowledge in geology. At present, the improvements and the developments of methods have reached such a state and the experience gained to date is so vast and varied that, to a certain extent, generalization is possible and many methods have become quite standardized. In prospecting for ore, the geophysicist either carries on his search over unknown areas or perhaps more often his problem is to follow known ore or ore zones into covered areas—the cover being either water, swamp, rock, soil, or glacial material. In the latter case, it is possible, when he works from the known into the unknown, to directly obtain correlations or good comparisons. This type of work can be performed almost by anyone with the faculty of sound judgment and a knowledge of geology.

Recent years' research and experience have brought to use the old magnetic methods to a very great extent. By using more sensitive instruments and a critical interpretation, in close co-ordination with geological knowledge, it has been possible to trace out formation contacts, solve structural problems, trace out structural features and sometimes directly indicate fault lines and magnetic mineralization, which often is associated with valuable ore bodies.

It has taken a very long time to obtain enough data and sufficient information to correlate and check predictions made as a result of the geophysical surveys, and the actual findings, in later exploration. I gave a review of many results in all parts of the world in an illustrated lecture at the meeting of the A.I.M.E. in New York, on February 24 [1944]. A brief summary of the conclusion follows:

Early Ideas

At first, the location of a conductor in the ground was thought very important, and each conductor was explored by trenching or drilling. Soon, however, it was found that there existed a great number of conductors in the ground. Sulphides of no commercial value, zones of shearing, or rocks with porosity and moisture content, higher than the surroundings, all give indications of conductors.

A great many methods were devised and tried out in an effort to distinguish the conducting bodies that were commercial, from those of no economic significance. Methods of outlining the shape of the conducting body were often helpful to the geologist in judging the worth of an indication. Many examples were shown of close agreement between predicted outline of ore bodies and the shapes found by later drilling and exploration work. Methods using phase determinations and employing varying fre-

* Consulting Engineer, Toronto, Ont., Canada. This discussion is reprinted by permission from *The Northern Miner*, Toronto, Canada, Issue of March 16, 1944.

quencies were tried out to identify the character, but many times the result was not so good. In a few cases, good results were obtained, however, but no assurance of successful identification of commercial ore can be obtained. However, by combining the use of magnetic, electrical, and sometimes seismic and gravity methods, it is, as a rule, possible to select the most favourable indications even when there are no outcrops or any geological hints as to their economic value. In most places, however, there are outcrops and these may help or guide the interpretation very considerably.

One very important factor is, however, that if no ore exists in the area, this can definitely be ascertained from the geophysical surveys, and thus large areas may be eliminated from further search.

My experience from the 25 years has definitely shown that the geophysicist searching for ore must confine his work to the location of physical anomalies and since there are no tricks involved in locating such anomalies the more frequent use of geophysical methods should be advocated. It is also suggested that everybody with some geological training should be given the chance to utilize these tools to aid them in their prospecting and geological mapping.

Education of Geophysicists

Simplification Advocated

An attempt at scientific elevation of the geophysicist has been brought out by the Education Committee of the American Institute of Mining Engineers, by requiring of the geophysicist a thorough knowledge of all branches of science, involving more than seven years of university work. A strong reaction, however, has set in against this suggestion: in fact the opposite stand has been taken and we are prepared to go much farther in the opposite direction.

Should the committee's program be adopted and sponsored by the A.I.M.E., the sound development and practical usage of exploration or applied geophysics, in fact its whole existence, would be in grave danger.

In the past, it has been difficult enough to keep exploration geophysics on an even keel, without this attempt at scientific elevation. It is most essential to avoid having exploration geophysics confused with "doodle bug" methods. The technique must be made clear to the client, so that he understands the possibilities as well as the limitations of the methods. Further, it must be convincingly demonstrated that the methods are based on sound scientific principles and that they are an integrating part of the work of the geologist, mining engineer and the prospector.

Experience has shown definitely that when too abstruse theories are advanced or too high-brow language used the client often associates geophysics with the magic of the divining rod and classifies exploration geophysics, in his mind, as another "doodle bug" method.

Should the committee's program be realized, the courses suggested are varying and so many, that only a super scientist could ever qualify, and experience has taught us that such a "scientissimo" quickly forgets the language that the practical man would understand. Thus, by following the program of the committee the door would be open wider for the humbug and the magician, since there would be no way for the ordinary mining man to distinguish between the language of the "scientissimo" geophysicist and that of the "doodle bug" charlatan.

Surely, it must be possible to outline a plan for the education of the geologist and mining engineer in exploration geophysics, without having them delve too deeply in the various sciences. I realize from the committee report that many geophysicists consider it essential to be highly technical and their academic tendencies are clearly shown in the education program thus outlined, but since it is the future mining engineer and geologist who are going to use geophysics exploration, it is these students who should be taught to understand and appreciate its value.

The students, however, cannot afford to spend too much time to learn about theories and fundamental sciences, beyond their standard curriculum. The students are willing to use the methods if they need them, and if they understand them; but therefore it does not necessarily follow that they should learn everything about the whole science of geophysics. By means of very brief courses the theory and practice of the methods should be taught using plain understandable language, and explaining their scope, as well as their limitations. The

technique is now so far advanced that it should be possible to hand the students instruments which they can operate themselves, and with which, later, as geologists or mining engineers, they should be able to obtain useful results without further assistance, when working with their own geological problems around the mine, or in the field.

Since we know, from our experience that we cannot indicate ore, it is left to the judgment of the geophysicist, using his knowledge of geology, to select the best anomaly for testing by drilling or otherwise. A good geophysicist may be characterized as a man who knows when to stop the geophysical work and take to drilling or digging.

Make Science More Popular

To my way of thinking, it is an absolutely wrong attitude taken by the education committee in making geophysics exploration more exclusive. On the contrary, it should be made more popular and it should be the property of everyone interested. The instruments should be put in the hands of practical people who live at the mines, or have their lives devoted to exploration or prospecting.

To the practical man it is not necessary to understand all the intricate details about the geophysical instruments and the various procedures. The geologist who works with his microscope takes the operation of his instrument for granted. He does not worry about which light theory is correct. He polarizes light with a movement of his finger and lets it go at that; and his polarized light is as good as anyone else's. Similarly, he determines refractive index and crystal structure by using tests developed, perhaps, by a highly trained physicist. Ninety-nine per cent of our best cooks use baking powder without the slightest concern over molecular changes that may result in the cake. How many car drivers can assemble their own automobiles and analyze their construction?

I have seen many examples of good work carried out by practical people using these methods and certainly their mistakes are not more frequent than those of the theoretically skilled scientists. To begin with the scientist geophysicist is generally unfamiliar with the local conditions when he starts his work although he performs his geophysical investigations with scientifically up-to-date methods and with very skillful operators.

A highly trained geophysical prospector, educated according to the pattern of the geophysics committee would certainly be too expensive to hire for a very long period, so that no mine or mining company could afford to have him take a very long time for solving a problem. It is sometimes necessary for a consulting geologist to stay for months at the property before he gets hold of the problem and can carry it to solution.

Consequently the scientist geophysicist's work, of necessity, must be of limited duration and then he can only obtain a sketchy knowledge of the geology and the conditions, and not very well delve into any intricate geological problem.

Therefore his interpretations must be taken as more tentative, as well as subject to later revisions, while the local man, using his geophysical apparatus whenever necessary, soon will be able to make quite definite and positive interpretations, since he is familiar with all local details and, as I see it, the local man would be able to perform better work and apply the methods to better advantage and make better interpretations if he only has a chance to learn enough about the methods and the instruments that he should use.

A Concrete Recommendation

My recommendation is therefore: to make available compact sufficiently sensitive scientifically sound instruments to begin with, magnetic and electrical and perhaps later on also seismic equipment that can be used by the prospector and the geologically trained man. These instruments could be made available at reasonable costs. Service by experts should be available so that the prospectors and the geologists could obtain the necessary help to start and carry out the work in the field.

The manufacturer of these instruments may also keep a good geophysicist available for consultations. Such a plan could be carried out now and be in full operation when our boys come back from the war. We know that after every big war prospecting is taken to by many of the returning soldiers and therefore by having these new tools available and easy to use we could serve a good purpose. A great number of new finds certainly will be made this way

and would also contribute to the post-war employment.

As far as the future is concerned, I doubt whether any of the present geophysical methods will ever be developed to directly indicate ore. However, the geochemical methods and certain combinations between chemical and geological methods now used might be the answer to our prayers for direct and more definite methods of determining the quality of the ore or its relative metal content.

Geochemical and spectrochemical analysis of minute content in ground waters, in soil or in plants and trees, living or dead, will be extremely important and I would venture to predict that in the very near future each mining or exploration company and each assay office will have its own spectroscope equipped for accurate chemical analysis, not only to guide the daily work in the mine, but also for identifying ores as well as for guiding exploration, geological mapping and the evaluation of geophysical indications. These methods, although they are still in their infancy, promise very much for the future. Radioactivity methods could also be helpful when sufficient facilities for radioactivity determination can be made available. They have already been used to a great extent in oil exploration and experiments have shown great promise for ore exploration also.

As for future surveys of large areas, the exploration for physical contrasts will be made from the air, using aeroplanes, helicopters, etc. Already electrical and magnetic methods have been designed whereby the instruments are carried in the aircraft and by automatic recording the location of anomalies is made in a simple enough manner. It should be possible in this way to cover, say, a square mile in an hour.

Later Discussion

Replies to Dr Lundberg.

J. B. Macelwane.*—Someone has said that if a person knows his subject well enough he can explain it in words of one syllable. The point is well taken and I think the converse is also true. If a person cannot explain a subject clearly in simple words, it is either because he has not sufficient command of the language, or he is not master of his subject.

Now it is obvious, it seems to me, that the remedy for both of these unfortunate conditions lies not in less education, but in more.

If Dr. Lundberg has met geophysicists who confused and discouraged prospective clients by their inability to talk the language of the mine owner or of the mining engineer or geologist, the fault most probably lay in the geophysicist's *lack* of sufficient training; but it may also have been the want of ordinary common sense, which no amount of education can supply.

It is hard to understand the position taken by Dr. Lundberg. Does he regret his own extensive training? Does he wish to say that he would have had greater success in geophysics if he had been only a mine hand with an instrument and a rule of thumb? As a matter of fact, I find it rather difficult to account for his presentation before this Committee on Geophysics of an emotionally distorted picture of the Report of the Committee on Geophysical Education, after the lapse of an entire year since the Report was read and discussed in its proper place, unless he honestly thinks he is handicapped by his knowledge and training and wishes to warn the whole profession against a similar fate.

I regret that I am obliged to disagree so emphatically with Dr. Lundberg's thesis—but I believe it would be dangerous if left unchallenged, both because of the inaccurate statements it contains concerning the recommendations made in the Report and because of the ultimate discredit that would be bound to fall upon genuine geophysics if Dr. Lundberg's recommendations were extensively followed out.

S. F. Kelly.*—The argument that a science and its practitioners can be improved by debasing the standard of educational preparation is indeed a strange argument to come from the pen of a man with the education of Dr. Hans Lundberg. In criticising the Committee report, moreover, he has to a certain extent set up a straw man to belabor. The statement that the Committee report recommends that

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a geophysicist possess a thorough knowledge of *all* branches of science is incorrect, as may be seen by referring to the tabulated curricula set forth in the 1942 and 1943 reports. An inspection of these curricula will also reveal the inaccuracy of the statement that *more* than seven years of university work is involved. The report of 1943 specifically provides a curriculum to "furnish the undergraduate with sufficient knowledge of geophysical science to enable him to assimilate rapidly and intelligently the various specific techniques of the art of geophysical prospecting should he choose, as so many will, to accept immediate employment in the industry." The additional three years suggested for graduate study differ in content but not in purpose from the three years spent by many students to acquire a doctorate in other lines of endeavor. To cavil at such graduate work is, by implication, to decry the value of the study and research that go into the pursuit of a doctorate in engineering, or in science, be it geology, physics, chemistry, or any other science. Such advanced educational preparation may not always be essential to a career on the research and investigative level, but its help is certainly invaluable.

Unquestionably, some elementary instruction on the techniques and instruments of geophysics should be given to geologists and mining engineers, so that they may better appreciate the value of these methods in their own work. This is a very different matter, however, from training them to use the instruments and apply the techniques as geophysicists. It does not come within the purview of the present discussion, which is concerned with the Committee report, confined to recommendations concerning the academic preparation for a professional career in geophysics.

Reduced to its essentials, the main argument presented by Hans Lundberg is that a geophysicist who has only a rudimentary knowledge of his art and science will be less likely to use high-brow language, and will more easily sell his services to a prospective client. This is equivalent, in related fields, to claiming that the less geology a geologist knows, the better can he sell his services to the mining engineer, and the less engineering a mining engineer knows the better can he sell his services to the company executives. Hardly complimentary to the intelligence of the prospective client!

The remedy for this particular difficulty is obviously not to demand less scientific training, but to require more thorough schooling in the correct use of simple English.

A geophysicist needs not only training in English, but also very thorough training in the fundamentals of the science in which he is working. Without such scientific preparation, supplemented by adequate experience, it is hardly possible for an operator to exercise that discrimination which is needed to differentiate the important from the unimportant, and to recognize that a given geophysical anomaly does not necessarily have a consistently unique cause. Placing geophysical instruments in the hands of operators lacking a theoretical background, and inadequately trained in techniques of field operation and interpretation, can have but one result,—to discredit geophysics and delay its expansion in the field of mining exploration. The idea that the possession of a magnetic instrument, for example, qualifies its owner to make geophysical surveys is evident in some mining quarters; but the fruit of this policy is now beginning to taste a little bitter to its followers. They find they are unable to plan their surveys so that the recorded anomalies are interpretable, and that they do not understand the significance of the anomalies they observe. Attempting to place the practice of the art and science of geophysics in the hands of the inexperienced and untrained creates a grave risk that these pseudo scientists will overplay the role of geophysics in mining exploration, and the inevitable reaction by the traditionally conservative mining companies can only redound to the discredit and discomfort of the capable and conscientious geophysicist.

H. LUNDBERG.—It is difficult to comprehend the idea behind the recommendations made by the Education Committee for the training of geophysicists, considering that the Committee is appointed by the American Institute of Mining and Metallurgical Engineers. The program outlined and the courses recommended seem to be intended to train geophysicists for teaching and pure scientific work, rather than practical field work. If the proposed program were carried through, no

doubt most students who had inclinations to study geophysics would be scared away.

The older mining men and geologists are also rather confused by the courses recommended and certainly are astonished by the almost complete lack of practical field work. While the courses proposed for the undergraduates are fair enough, stratigraphy and sedimentation should be taught rather than stratigraphy and paleontology, and the study of ore minerals and ore bodies in place of crystallography and mineralogy. Furthermore, structure and metamorphism would seem more suitable than petrography.

I doubt very much whether a man specializing in geophysics could be able to practically pursue all branches in his profession, but there should be a dividing up after the undergraduates' courses have been plotted, into different specialties; for instance, a man who wants to go into prospecting for oil should get an entirely different training from that of the man prospecting for ore minerals.

Leaving the oil prospecting alone and discussing the ore mineral prospecting, which is my specialty, it has been made too much of a mystery to suit clients, mining engineers, geologists, as well as the students. Geophysicists carrying out prospecting for ore minerals should first and last know elementary geology and have specialized in structure and metamorphism. A study should be made of ore minerals and ore bodies. Useful information about ore bodies can easily be understood without much detail knowledge of the composition, crystal structure, etc., of the minerals, and in education there should be stressed the importance of the relationship between the physical measurements and the geological setting—and, last but not least, a great deal of field practice would be required, not only for geological studies, but for giving the student practice and experience in applying the theories to the methods under widely differing conditions and for different types of deposits.

Briefly, the Mining Engineer and the Geologist must be told, in concentrated courses, what geophysical methods are and what they can accomplish. I want them to like geophysics and to use it and I do not want them scared away. I think it should be a special aim of the American Institute's Education Committee to see to it that this purpose is accomplished, rather than to outline lengthy curricula for the training of exceedingly specialized scientists and teachers.

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(NOTE: In this index the names of authors of papers and discussions and of men referred to are printed in SMALL CAPITALS, and the titles of papers in *italics.*)

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